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ADVISORY GROUP FOR AEROSPACE RESEARCH & DEVELOPMENT
7 RUE ANCELLE, 92200 NEUILLY-SUR-SEINE, FRANCE

AGARD CONFERENCE PROCEEDINGS 581

Advanced Architectures for Aerospace Mission Systems

(Architectures futures pour l'avionique de gestion de mission)

Papers presented at the Mission Systems Panel 6th Symposium held in Istanbul, Turkey, 14-17 October 1996.

NORTH ATLANTIC TREATY ORGANIZATION

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North Atlantic Treaty Organization
Organisation du Traité de l'Atlantique Nord

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Advanced Architectures for Aerospace Mission Systems

(AGARD CP-581)

Executive Summary

The sixth symposium of the Mission Systems Panel was prompted by major changes that are expected in the configuration of future weapon platform mission systems. At present these usually consist of a variety of complex and costly stand-alone functions (EW, fire control, communications and so on) but there is a move towards more efficient, effective and affordable advanced architectures which embrace the whole mission systems suite and are characterised by close functional integration and greatly improved data interchange and management. As well as architectural concepts, applications, and technologies, the symposium included as a topic the use of commercial off-the-shelf components (COTS) and a concluding discussion on the impact of advanced architectures on affordability.

Key issues addressed by the symposium were:

- The high cost and complexity of present mission systems - now approaching 40% of total weapon platform cost;
- The need to integrate the functions performed by the platform in order to reduce cost and weight penalties incurred by individual, specialized systems;
- The improvements in reliability, maintainability, and functional reconfigurability from common digital modules, common high-level software and shared RF and EO apertures;
- The extent to which flexible hardware and software architecture could lead to easier upgrades and improved mission reliability.

The symposium covered a wide range of applications and highlighted the developments taking place on both sides of the Atlantic in signal and data processing/communications and related areas of advanced information technology. These developments hold out the promise of highly integrated mission systems that will be much more adaptable, fault tolerant and affordable than present systems. Much of the hardware and software technology is commercially inspired, making the drive towards utilization of COTS components and technologies a feasible goal, though account must be taken of those key areas of avionics in which the requirements will remain in advance of commercial developments, and of military systems' extended life spans to ensure they do not end up with obsolete hardware and software standards that are no longer supported in the market place.

The symposium was rated by the participants from significant to extremely valuable.

Architectures futures pour l'avionique de gestion de mission

(AGARD CP-581)

Synthèse

La décision d'organiser le sixième symposium du Panel AGARD des systèmes de conduite de mission a été motivée par les grands changements qui sont attendus dans la configuration des futures plates-formes de systèmes d'armes. A présent, celles-ci consistent en général en un grand nombre de fonctions autonomes complexes et coûteuses (EW, conduite de tir, communications etc.), mais une tendance se dessine en faveur d'architectures avancées plus efficaces, performantes et abordables. Ces architectures couvrent l'ensemble des équipements de conduite de mission et sont caractérisées par une intégration fonctionnelle très poussée, une meilleure gestion et un meilleur échange des données. En plus des applications, technologies et concepts architecturaux, le symposium a examiné la question des composants du commerce (COTS) lors d'une discussion de clôture sur l'impact des architectures avancées sur le concept du coût de possession acceptable.

Les principaux sujets abordés lors du symposium étaient les suivants :

- le coût élevé et la complexité des systèmes de mission actuels - il avoisine 40% du coût global de la plate-forme d'armes ;
- la nécessité d'intégrer les fonctions remplies par la plate-forme afin d'atténuer les effets pénalisants en termes de coût et de poids pour les systèmes individuels spécialisés ;
- les améliorations en ce qui concerne la fiabilité, la maintenance et la reconfiguration fonctionnelle à partir de modules numériques communs et de logiciels communs de haut niveau à ouvertures RF et EO partagées ;
- la mesure dans laquelle les architectures matérielles et logicielles souples pourraient faciliter les extensions et améliorer la fiabilité opérationnelle.

Le symposium a couvert un grand éventail d'applications possibles en mettant l'accent sur les développements en cours des deux côtés de l'Atlantique dans le domaine du traitement du signal et des données, des communications et les domaines y associés des technologies avancées de l'information. Ces développements promettront d'aboutir sur des systèmes de conduite de mission plus souples, à meilleure tolérance de pannes et plus abordable financièrement que les systèmes actuels.

Bon nombre des technologies matérielles et logicielles ont une vocation commerciale. L'objectif de la mise en œuvre de ces technologies et composants COTS est, par conséquent, tout à fait réalisable. Cependant, dans cette démarche, il devra être tenu compte, d'une part des domaines clés de l'avionique où les caractéristiques techniques demandées seront toujours en avance sur les développements commerciaux et, d'autre part, des cycles de vie prolongés des systèmes militaires. Ceci afin d'éviter la situation où les normes du matériel et des logiciels utilisés seraient dépassées; ce qui aurait des conséquences négatives sur leur maintenance.

Les participants à ce symposium l'ont jugé pour le moins digne d'intérêt et même d'une très grande valeur.

Contents

† Not available at time of printing.

Theme

Mission systems in the past were developed primarily as stand-alone, dedicated suites to perform a single function such as EW, fire control, communication, etc. It is becoming increasingly clear that future mission systems must be designed from the perspective of the total set of functions that will be performed by the platform. This is being driven by the fact that the cost of mission systems has risen dramatically in recent years. For example, the mission systems cost for aircraft is approaching 40% of the total weapon system fly-away costs. Furthermore, the weight of individual specialized mission systems is becoming exorbitant.

Also, higher reliability, maintainability and the ability to reconfigure the functions performed are definite advantages of advanced architectures. Thus, future mission systems will be characterized by a robust architecture, common digital modules, common high level software utilizing a standard language and shared RF and EO apertures across functions. The architecture will define the interfaces between the common and shared modules used to implement the required functional performance. The architecture will also define the interfaces to be used for the software modules. A flexible hardware and software architecture will permit easy upgrades through incorporation of ever-improving hardware and software technology. Advanced architectures will also permit substantial improvements in mission reliability due to the great flexibility in reconfiguring the system hardware and software to minimize the impacts of module failures. An integrating element uniting the components will be provided through sensor and data fusion/correlation processes that will be an essential element of the advanced architectures.

Thème

Dans le passé, les systèmes de conduite de mission étaient développés principalement comme systèmes autonomes spécialisés, destinés à remplir une seule fonction telle que la guerre électronique, la conduite de tir, les télécommunications etc. Il semble de plus en plus évident que les systèmes de conduite de mission futurs devront être conçus pour l'ensemble des fonctions qui seront à exécuter par la plateforme. Cette approche s'explique par le fait que le prix d'achat des systèmes de conduite de mission a augmenté de façon sensible au cours des dernières années. A titre d'exemple, le coût typique d'un système de mission aéronautique moderne atteint presque 40% du prix en état de vol du système d'armes auquel il est associé. En outre, la masse physique des systèmes de conduite de mission individuels spécialisés pose de plus en plus de problèmes.

Par contre, les architectures avancées peuvent s'attribuer un certain nombre d'avantages concrets tels que la fiabilité et la maintenabilité améliorées, ainsi que la possibilité de reconfigurer les fonctions exécutées. Ainsi, les futurs systèmes de conduite de mission seront caractérisés par des architectures robustes, des modules numériques communs, des logiciels de haut niveau communs écrits en langage standard, ainsi que des passerelles RF et EO entre les fonctions. L'architecture choisie définira les interfaces, entre les modules communs et partagés permettant d'obtenir les performances fonctionnelles demandées. L'architecture définira également les interfaces à adopter pour les modules logiciels. Une architecture logicielle et matérielle souple facilitera les extensions par l'intégration de technologies logicielles et matérielles évolutives. Les architectures avancées conduiront à des améliorations substantielles en fiabilité opérationnelle, étant donné la grande souplesse de reconfiguration du matériel et du logiciel systèmes, qui permettra de minimiser l'impact des pannes des modules. Enfin, les techniques de détection et de fusionnement/corrélation des données seront un élément essentiel des architectures avancées ; elles joueront un rôle intégrateur, permettant de relier les différents composants des systèmes.

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Le Panel tient à remercier les Délégués Nationaux de la Turquie près l'AGARD de leur invitation à tenir cette réunion à Istanbul et de la mise à disposition de personnel et des installations nécessaires.

TECHNICAL EVALUATION REPORT

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INTRODUCTION

The Sixth Symposium of the Mission Systems Panel, on Advanced Architectures for Aerospace Mission Systems, was held in Istanbul, Turkey on 14-17 October 1996. It was prompted by the need for major change in the configuration of weapon platform mission systems (at present, generally a collection of stand-alone systems dedicated to separate functions of EW, fire control, communications and so on) which are becoming excessively complex and costly.

The main thrust of the Symposium was towards more efficient and effective advanced architectures that will embrace the whole mission systems suite, emphasising functional integration and data interchange and management. As well as architectural concepts, applications, and technologies, the symposium included as a topic the use of commercial components and a concluding discussion was devoted to the impact of advanced architectures on affordability.

Key issues that were planned to be addressed by the Symposium were:

- The high cost and complexity of present mission systems – now approaching 40% of total weapon platform cost.
- The need to integrate the functions performed by the platform in order to reduce cost and weight penalties incurred by individual, specialized systems.
- The improvements in reliability, maintainability, and functional reconfigurability from advanced architectures that utilize common digital modules, common high-level software and shared RF and EO apertures.
- The extent to which flexible hardware and software architectures could lead to easier upgrades and improved mission reliability.

KEYNOTE ADDRESS

In his Keynote Address, "Requirements for Advanced Avionics Systems Architectures," Dipl.-Ing. Jochen Potthaus, Director, Bundesmat für Wehrtechnik und Beschaffung (BWB), GE, set the scene for the papers that followed by focusing on the requirements for advanced avionics systems, architectures, interoperability and standardization, as he saw them, and their implications for current ways of contracting and building equipment. Referring to the rapidly-evolving capabilities of sensors and real-time computing systems, he reviewed the advanced operational capabilities and new functionalities they will make possible, together with their contribution in helping to meet the demands of the Alliance for flexibility, mobility and interoperability.

The potential of a total system approach to avionics systems integration for containing costs, together with advanced information handling and the use of commercial off the shelf components (COTS) were highlighted as important themes of the symposium. He summarised the advantages achievable by advanced avionics systems under the headings: system survivability, system availability, multimission capability, mission success probability, interoperability and deployment, and life cycle cost.

He rounded off his Keynote Address by stressing the need for cooperation and exchange of information between the NATO nations and expressing his appreciation to AGARD and the contributors to the present symposium.

SESSION I: TECHNOLOGY OVERVIEWS

Mr Larry Ott, US, (Symposium Chairman) opened the session by highlighting three areas of concern for the symposium: architectures, information management, and COTS. As an example for later discussion he commented on the drive towards open architectures and the potential difficulties of efficient implementation in existing aircraft and of commonality in architectures across different classes of aircraft. Also, information management raises difficult questions regarding the quantity and availability of information and associated technology challenges. COTS utilisation raises a number of difficult issues in military systems' implementation, such as security and fault tolerance.

The first paper of the session, "Advanced Architectures – Where are We Going?", by Domae, Logan and Viney, of Northrop Grumman, US, was presented by Terry Domae. It addressed the issues of advanced architectures from the perspective of the Joint Strike Fighter, and the evolution of open systems from the PAVE PACE and PAVE PILLAR programmes of the 1980's. Long term technology trends in digital sensor processing and preprocessing, analog-to-digital converters, lightwave signal distribution and routing technology, and portable and supportable software, provide keys to affordable avionics advances in areas such as future waveform-independent electronics modules capable of supporting multifunction apertures.

The authors concluded that integrated architectures will become the rule for new systems or major upgrades and noted the trend towards digitization of previously analog functions with associated enhanced system reprogrammability, plus the evolution of distributed integrated systems.

The paper given by Mike Williams that followed, "Information – the Warfighter's Edge", by Williams and Collier of Lockheed Martin, US, was subtitled "The Joint Strike Fighter and System-of-Systems", which indicated the focus of their paper on the maximum utilization of information systems in forthcoming military aircraft to improve their capability. Concerns with affordability, lethality, survivability and supportability were discussed in terms of the trade-space of ISR (Intelligence, Surveillance and Reconnaissance), C^4 (Command, Control, Communication and Intelligence), Onboard Systems, and CONOPs (CONcept of OPerations). The authors' vision of the emerging JSF battlefield – elaborated in a description of the System of Systems requirements process – is one in which ISR and C^4 assets are fully integrated with on-board systems. They concluded that a completely autonomous mission capability for tactical aircraft is no longer affordable nor necessary, and that on-board sensors can be made individually less complex, given the ability of advanced on-board avionics systems to correlate large amounts of information.

In reply to a question from the Session Chairman regarding non-concurrent information, the author stressed the need to balance all elements of the trade-space, taking account of the timeliness and accuracy of off-board information, and the need for time-tagging and utilization of multiple sources for data fusion.

The final paper of this session, "COTS Joins the Military", by Anderson and Stevens of Lockheed Martin, US, was given by Larry Anderson who presented an analysis of COTS products and NDI (Non-Development Items) in terms of their ability to meet affordability requirements. However, to achieve the potential of COTS/NDI economies of scale, several factors must be considered, including defence industry involvement in commercial development, and the need for continuous technology insertion in place of present lengthy upgrade intervals.

The authors cited their company's participation in the US Navy sponsored HSDTN (High Speed Data Transfer Network) working group, which adopted the IEEE 1596-1992 Scalable Coherent Interface (SCI) as a standard backplane network in order to eliminate the lack of bandwidth and scalability of "party line" backplane buses. Their COTS-based P^3I strategy has introduced significant changes in software architecture including for example, commercial multiprocessor systems using SCI in shared memory management and cache control. However, the authors also describe a significant SCI-based scalable multi-processor system (SMPS) based on non-commercial development of a high-bandwidth, fault-tolerant matrix switch.

SESSION II: ARCHITECTURES FOR MISSION SYSTEMS MODERNIZATION

The first paper of this session, "Department of Defense Perspective on Open Systems Architecture", by Lt Col Glen T Logan of the USAF, addressed one of the major issues raised in the previous session. Col Logan began with a summary of the background thinking to current DoD policy in this area, resulting from reduced US defense budgets and the recognition that it can no longer "go it alone". The Open Systems Joint Task Force (OS-JTF), set up in response to a 1994 policy memorandum from the Under Secretary of Defense, was the main subject of his paper.

The Task Force's activities (publicised on its Internet World Wide Web Home Page) cover three main activities: training, standards, and demonstration programs. The author mentioned two demonstration efforts currently being planned: the AV-8B Open System Core Avionics Requirements (OSCAR) which would be expected to pay for itself in five years, and the F-15 Multi-Purpose Display Processor; plus the related Open Systems Ada Technology (OSAT) demonstration in association with the Ada Joint Program Office and the Joint Strike Fighter Program Office.

The author agreed, in response to questions, that there were problems with changing industry standards (for example the probable eventual disappearance of VME support) and the suitability of commercial devices for the military environment. Both questions pointed up the need for avionics industry involvement in the early stages of development, when any additional cost could be minimised.

The next paper, "Modular Avionics System Architecture Definition in the EUCLID Research and Technology Programme 4.1", by A Marchetto of Alenia Aeronautica, IT, described what has been the first programme of a more general Modular Avionics initiative (CEPA 4) under the auspices of EUCLID (EUropean Cooperation for the Long term In Defence). The timeframe for the study assumed applications in the period 2005-10 (at least for retrofit – though road maps for a new fast jet suggest c.2015). Significant features of the resulting General System Architecture include a matrix switch network (MSN) (similar in principle to that described in the paper by Anderson and Stevens in Session I) and modular integrated digital processing blocks which include high bandwidth digital signal processing. The implications of the latter, for RF sensors in particular, is important in that it shifts upstream the interface between sensors and the general-purpose configurable processing system.

The final paper of the session placed the earlier two papers usefully in context, showing the relevance of those concepts for modernising existing mission systems, as well as pointing the way towards future cost-effective avionics. The paper, "When do Advanced Avionics Architectures Make Sense for Upgrading Aging Aircraft?", by Kreuger and Venner of Wright Patterson USAFB, was presented by Sqdn Ldr Robert

Venner, RAF. The authors provided a valuable user perspective, arguing that by replacing ageing federated avionics systems on older aircraft with integrated modular avionics (IMA) many of the problems due to the huge variety of components in existing federated avionics systems could be overcome. As an example of the scale of the problem, the USAF support some 83 types of aircraft with more than 1,000 different avionics systems, employing 5,000 line replaceable units and 70,000 shop replaceable units. They anticipated that IMA would yield major improvements in spare parts obsolescence, reliability and upgrading, whilst providing growth capacity and enhanced performance. Speculating on the technology needed to implement IMA, they indicated several critical areas including, in addition to the software and backplane issues covered in the symposium, the equally important areas of packaging and cooling.

SESSION III A: ARCHITECTURAL CONCEPTS

The first paper of the session, "The Future of Avionics Architectures" by Reed Morgan of Wright-Patterson AFB, provided a general survey of technology trends and future projections. He illustrated the progress from independent single-function electronics of the 1940s-50s, through federated systems of the 1960s-70s with multi-function displays and controls, and integrated avionics systems of the 1980s-90s employing common integrated processors, towards advanced integrated avionics, post-2000, with ASDN switching of sensor outputs to shared "supercomputer" digital signal and data processing. His projection for future architectures envisages integrated RF sensor systems and integrated EO systems, shared apertures/antennae, and optical heterodyne receivers, feeding a unified digital avionics network with a COTS-based common integrated processor, via optical switches and shared digital IF. His projection depends on the development of new photonic building blocks, digital signal and data distribution across backplanes and changes (greater avionics industry involvement?) in the COTS market place.

In the discussion that followed, the author replied to a question on the future scale of software growth by agreeing that, on present trends, it was becoming unsustainable without some breakthrough in software generation (the F-22 software has been measured in tens of millions of lines of code).

The main concern of the next paper, "Technology Transparency in Future Modular Avionics Systems", by Edwards, (British Aerospace, UK) and Connan (Dassault Aviation, FR) was with the problem of obsolescence caused by the rapidly-evolving technology employed in IMA. The paper, presented by Ross Edwards, suggested that greater transparency, as a key architecture feature for specifications and system design, would help mitigate the problems. It requires open IMA standards, endorsed and supported by industry and governments; whilst the market also needs to be led in the right direction by standardization programmes such as ASAAC (Allied Standard Avionics Architecture Council). Mr Edwards, in answer to a question, agreed there was no non-avionics commercial electronics involvement in ASAAC at present, but noted that many of the same people were involved in both military and commercial standards and there was awareness of the market potential of leading military standards.

SESSION III B: ARCHITECTURAL APPLICATIONS

The first paper of this session, "Integrated Modular Avionics Architecture Concepts Demonstration," by Potthaus, BWB, GE and Klöckner, Sprang and White, ESG, GE, was presented by Gordon White. The demonstration programme embraces key elements of an IMA concept (related to the ASAAC activities referred to in other papers, such as that described by Marchetti in Session II) including the communication network and the software architecture. He described a functioning platform which has been used to investigate, demonstrate and validate the communication network concept (implemented in the first instance, for purely concept demonstration purposes, as a 4x4 matrix switched network based on commercial off-the-shelf components). The software architecture demonstration includes fault management aspects. Future developments are intended to extend the software architecture and the communication network, including the eventual application of an optical switch matrix. In answer to a question on processing loads, he said that benchmarking was only just beginning but the programme was expected to provide valuable confirmation that the overheads associated with the network implementation, interface configuration, etc. would be acceptable for future applications.

In the paper that followed, "An Enhanced Modular Avionics Architecture for Military C^4I", by R H MacDonald of the Norwegian Defence Research Establishment, the author started with the comment that COTS was particularly important for smaller countries. It was the inspiration for the new design philosophies which focused – as in other papers – on open systems architectures, new communications technology, and the re-use of applications software. His analysis of costs/benefits was illustrated by a comparison of existing and future communication standards, from Ethernet, through FDDI and ATM to SCI, in which, for example, he showed a near-tenfold progressive improvement in latency of information. He also stressed the importance, when applying the COTS philosophy, of open standards and continuous upgrading, to help avoid the severe problems of obsolete and unsupported commercial standards.

The paper on the "Experimental Analysis of the Anomalies in the Structure of Radomes on their Performance", by Çelikel (Turkish Air Force) and Görür (Niğde University), TU, though not a main-

stream Symposium topic, was a useful reminder of the problems and limitations of real sensors. The paper, presented by Sadik Çelikel, described the experimental results of fitting Mica plates at various locations on a full-size radome and measuring the resulting transmission and boresight errors. Development of the test facility and the test results have provided insights into the effect of radome imperfections which can provide a guide for repair and maintenance.

The next paper, by Rico and Gallego of the National Aerospace Research Establishment, SP, focused on a specific project. "CAPRICORNIO Launcher: an Approach to a Modular and Low Cost Design" was an interesting example of some of the issues involved in practical software development for embedded computers. The objective of the CAPRICORNIO programme is to provide a capability for launch of small satellites into low orbits. The paper described the on-board guidance and control computer (which uses two commercial boards based on standard 32 bit processors connected by a VME bus, and an RS422 interface with the thrust vector and aileron actuator systems), plus the ground control system. They are being developed in the first instance for the ARGO test vehicle which is being used to demonstrate the systems prior to the full-scale CAPRICORNIO launcher. Software development has emphasised low cost, modularity and flexibility to facilitate migration from ARGO to CAPRICORNIO. The software requirements were developed using structured analysis techniques and implemented in Ada. The software development environment embraces a variety of tools, including the LabVIEW graphics tool which has been used for the GCS software, a prototype of which has been tested by the user.

The main concern of the final paper in this session, "Signature Avionics – Signature Optimised Operating of a Stealth Aircraft" by Hurst, Knappe and Benninghofen of Daimler Benz Aerospace, GE, was with avionics that avoid compromising the signature of stealth aircraft, or which take advantage of their stealth characteristics, or which coordinate stealth design and avionics functions. The authors described the Dasa Software Technology Environment for rapid prototyping and initial testing, followed by integration in their Avionics Testbed which provides a cockpit simulation with external scene representation. An example of a practical application was presented in the concept of "fly by signature" which aims to minimise exposure of stealth aircraft to air defence systems by flight path optimisation, taking into account geographical threat models and the aircraft's own signature. In the discussion that followed, the authors indicated the aim was to provide a real-time capability which would have practical applications in mission planning and execution.

This session was noteworthy for the range of aerospace applications covered, including software development for satellite launcher guidance and control.

SESSION IV A: ADVANCED MISSION SYSTEMS TECHNOLOGIES

This session comprised four papers, two of which were concerned with a critical element of advanced architectures – network switching.

The first paper, "A Multiservice Switch for Advanced Avionics Data Networks", was by Rosen, Turner, Gershman and Birmingham of the US Naval Air Warfare Center, and Phipps and George of FAMU-FSU College of Engineering, Tallahassee, US. It was presented by Vladimir Gershman. He first outlined the requirement for a unified data network to replace a variety of existing interconnects and to include sensor/video. In addition to high data transfer rates, fault tolerance, COTS utilization, low power, low cost and low weight, the unified network must be capable of adapting to the conflicting capabilities of the individual networks it replaces. The IEEE 1596-1992 SCI (Scalable Coherent Interface) standard has provided the basis for the MSS and a prototype produced, based on the commercial Dolphin LC-1 link controller chip. It has successfully demonstrated its capacity for handling varying types of interconnect requirements, such as streaming data at one extreme and low-latency burst messages at the other. It has also proven equal or superior in throughput to individual conventional network topologies.

The next paper, presented by David Aupers was also concerned with high speed interconnection systems for modular avionics. "Simulation of a Cell Switched Network for the Control of a Switch Matrix in a High-Speed Avionics Network", by Aupers, Heerink and Wellink of NLR, NL, described research being carried out as part of a EUCLID research and technology programme (RTP 4.1 – as also were papers in Sessions I and II). The research programme has modelled and simulated an optical switch matrix for circuit-switched point-to-point connections, with a Cell Switched Asynchronous transfer mode (ATM) network to control the switch and provide transfer of lower-rate data, files and status messages. ATM (used also in the B-ISDN successor to the ISDN standard) was selected after comparison with 1553, FDDI and SCI on the basis of technical suitability, and the commercial and academic availability of models and technology. The results have provided useful indications for practical implementation of the system.

The next paper, "Multifunction Radio Systems for Multinational Systems" by G Mey (Ministry of Defence) and P H Reitburger (Rhode & Schwarz), GE, was presented by Dr Peter Reitburger. The paper described the requirements, design principles and architecture for multi-function radios capable of handling a diversity of standards. The architecture embraces five modules (antenna system, receiver/transmitter, presignal processing, data processing, and man-machine interface) each capable of a variety of modes and functions. The advantages of such equipment were shown in an example of an aircraft mission, in which

the equipment could function with different RF waveforms (HF, VHF, UHF, JTIDS, MLS/DME-P, Radar Altimetry, GPS, NIS, and SATCOM) that at present require individual receivers/transmitters. The authors stressed the advantages for multinational NATO operations.

The final paper in this session addressed many of the same issues as the paper by Williams and Collier in Session I, in particular the use of external real-time information to enhance on-board avionics performance. Richard Kirchner presented the paper on "Rapid Targeting and Real-Time Response" by Searle, Kirchner, Fincher and Armogida of the US Naval Air Warfare Center, China Lake. The paper's sub-title, "The Critical Links for Effective Use of Combined Intelligence Products In Combat Operations," gives an idea of the main thrust of the paper, which follows demonstrations by the US Navy (Forward Hunter) and Air Force (Goldpan) of "Real-Time into the Cockpit/ Offboard Targeting" (RTIC/OT). This operational concept aims to improve mission planning time and the response to rapidly changing battlefield conditions, by providing real-time inputs to aircrew from a variety of sources. These would include for example, UAVs, theater reconnaissance aircraft, satellites, etc., directly transmitted – or relayed – to strike aircraft. An important element in the RTIC/OT concept is provision of imagery to the cockpit to assist in target acquisition, as shown in the joint exercise, Arid Hunter. This exercise demonstrated that major improvements could be achieved when imagery was input to the cockpit and combined with the use of GPS, compared to using either GPS alone or killbox coordinates. The RTIC/OT concept is being developed through a number of USN and USAF demonstration programmes. The question and answer session at the end of this paper raised several interesting points, particularly in regard to imagery aids for target acquisition. The author agreed that different conclusions could be drawn in the case of autonomous weapons where the target coordinates are known with high accuracy, but was not convinced by a suggestion that on-board platform sensors correlated with pre-stored target imagery might do the whole job equally well in manned aircraft, because of the limitations in quality or format of on-board sensor imagery.

SESSION IV B: PROCESSOR TECHNOLOGY

This session contained four papers of widely varying subject matter. The first paper, "Integrated Processing", by Farmer, Robinson and Trujillo of Hughes Aircraft Company, US, and presented by Edward Trujillo, started with an overview of the requirements and aims for modular integrated avionics, covering much of the same ground as earlier papers (integration, modularity, commonality, open systems, COTS). The author went on to describe the evolution of avionics standards and supporting technology via second generation DAIS, third generation Pave Pillar (represented by the Common Integrated Processor for the F-22 Advanced Tactical Fighter avionics), to fourth generation Pave Pace. The written paper describes the Hughes Modular Processor for the F-22, based on open standards and commercial components (e.g. SAE 4710 PI Bus and Intel i960 RISC processor) and a single chip upgrade for an existing multi-chip processor. An important conclusion of the paper, as presented, was the recognition that to extract the maximum value from COTS it is necessary to consider carefully what additional purpose-designed elements need to be developed.

"A Modular Scalable Signal Processor Architecture for Radar and EW Applications", by Keller, Rabel, and Schmitt of Daimler Benz Aerospace, GE, was presented by R Rabel. The paper described the Advanced Programmable Signal Processor (APSP) developed by Dasa in support of ASAAC/Euclid, as part of a strategy for achieving proven high performance systems based on off-the-shelf technology. The APSP consists of expandable arrays of programmable modules (based on clusters of Texas Instruments TMS320C3x processors) and semi-programmable modules (containing dedicated processing hardware such as FFT processors), connected by a VME bus and associated modules, and a Data Transfer Network. The paper describes the operating system, APOS, and applications of APSP, including a real-time SAR processor with eight Doppler processors. In his answers to questions, the author made it clear that the architecture described is only one of the ASAAC candidates. He also said that the APOS level allows for upgrades and – as stressed in the paper by Edwards and Connan in Session IIIA – a high degree of transparency.

The next paper, "A Survey of Advanced Information Processing (AIP) Technology Areas for Crew Assistant System Development", by Kuru and Akin of Boğaziçi University, Istanbul, TU, described work on a part of the EUCLID RTP 6.5 Crew Assistant project, in collaboration with Alenia, Dasa and NLR. The paper, presented by H L Akin, covered the methodology of the survey, including choice of evaluation criteria (functionality, reliability, performance, modularity, integration with other technologies, engineering methodology, maturity/next generation, and availability) and the results of the survey, covering software engineering methodologies; verification, validation and certification; knowledge-based systems; distributed artificial intelligence; learning systems; planning; model-based reasoning; case-based reasoning; object-oriented databases; and finally a summary of AIP technologies used in existing programmes. From their comprehensive survey, they concluded that readily available, mature AIP technologies had been identified that can provide the required CA capability.

The main subject of the last paper in this session, "New Sources of Geographical Data for Automatic Identification Application" by Peufeilhoux, Cazeneuve and Hervy, of Thomson-CSF, FR, was the combined

use of various geographical data. The paper, presented by Philippe Hervy, addressed the problems of terrain identification and recognition in relation to cruise missiles and long range aircraft operations. The sources of data discussed included 1/15,000 scale national topographical maps, satellite images, and global digital data bases such as the 1/100,000 scale DCW (Digital Chart of the World), and 1/200,000 scale VMAP (Vector Map). An example was given of air-to-surface target identification utilizing geographical data with a purpose-developed algorithm. The paper, though not strictly aligned with the session's title of "Processor Technology", was interesting as an example of data fusion to maximise the utility of alternative information sources.

SESSION V: INFORMATION PROCESSING APPLICATIONS

This was the longest session of the symposium, with papers focused mainly on avionics applications to mission planning, management and execution.

The first paper, "Mission Management System Design", by Sassus, Bonhoure and Marito of SEXTANT Avionique, FR, was presented by Fabienne Bonhoure. The objective of the work described was to improve mission effectiveness in a high workload environment by providing active en-route planning and decision-making aids with, for example, automatic prompts as necessitated by the tactical situation and mission deviations. The paper, subtitled "A Technical and Methodological Approach", first defined the mission management function, followed by descriptions of the software architecture and development methodology, and implementation in a mission simulator. The programme is to be developed to include a wider range of missions and theatres, and on-board implementation aspects. In reply to questions regarding pilots' willingness to use automated on-board mission management and on the realism of the simulation, the author emphasised the element of choice in the presentation and use of pilot prompts, and the immense value of pilots' participation in the programme.

By contrast, the second paper, "Mission Planning Systems: Cubic Multipliers", by de Moel and Heerema of NLR, NL, was concerned with the multiplier effects of improving the ground element of mission planning. The paper, presented by R P de Moel, considered three aspects: firstly, the quality of information – in particular, geographical data – for mission planning and its effect on mission execution; secondly, the importance of uniform training and of training exercises; and thirdly, the technology of training and simulation. The paper focused on geographical data sources with the emphasis on Nato Standard Agreements (STANAGs) and on the evolution of NLR's mission planning workstations which started in 1979 and led to the semi-operational CAMPAL (Computer Aided Mission Preparation at Airbase Level) workstation of 1991 to 1994, with 3D colour graphics, high resolution display and colour hard copy unit. The operational mission support system, currently being developed, is known as PANDORA (Planning of Aircraft Navigation for Defensive, Offensive and Reconnaissance Airtasks). A question regarding the comprehensiveness of geographical data and use of satellite imagery was answered with an acknowledgement that development was an ongoing process and Nato image standards would be incorporated as they appeared; and in answer to a further question on in-flight re-planning, the author referred to future developments with a timely reminder that it was first necessary to solve today's problems.

The English title of the next paper, as given in the programme, "Mission Recording and Restitution", translated from the original French, "Système d'enregistrement et restitution de Mission", would have been better translated as *mission recording and playback* – playback being the main purpose of the system. The paper, by F X Parisot of SAGEM, FR, describes the overall functional scheme, comprising the on-board interface box BISE (Boîtier d'Interface Système – Emports) which takes inputs from the mission computer (including mission planning input data) and sensors, plus video recording and cockpit displays. Among other functions, the BISE provides time multiplexing of video inputs and generation of time markers for harmonising digital data. The video recorder data is combined with mission computer data in the playback system for post-mission analysis. The author also expanded on the written paper with a description of the further development of on-board real-time replay as a mission aid, involving additional equipment for video compression/decompression and a short term drum recorder, the equipment weighing an additional one kilogramme with a volume of one litre. Further development is aimed at completely digital recording.

The paper on "A Generic Architecture for Crew Assistant Systems" by Urlings and Zuidgeest of NLR, NL, was presented by Pierre Urlings. In it, he outlined the background and requirements for crew assistants, emphasising the enhancement of crews' system and situational awareness, and some results of work carried out as part of EUCLID RTP 6.5 – a multi-national effort directed towards CA concept demonstration. The functional architecture is based on a division into crew assistant functions that correspond to crew functions, either uniquely, or grouped where appropriate. Each CA function follows the same basic data flow of collection, assessment, decision and presentation, with shared management of data input, control, coordination and presentation to displays and controls. The author described the CA concept as a rich area for AIP (advanced information processing), citing the two main approaches to DPS (distributed problem solving) – distributed knowledge sources (blackboard system) and multi-agent systems – as indicative of the technology and its maturity for next generation crew assistant

applications. Questions to the author were concerned with development and certification, issues that were addressed in the related paper by Kuru and Akin in Session IVB, and the topic of crew overruling and its implementation, whose extreme importance was well recognised by the authors.

The following paper was also devoted to the topic of crew assistants. "Perspectives of Crew Assistance in Military Aircraft through Visualizing, Planning and Decision Aiding Functions" by Schulte and Klöckner of ESG, GE, was presented by Dr Axel Schulte who described the CAMA (Crew Assistant Military Aircraft) system. This knowledge-based expert system, developed in cooperation with the University of the German Armed Forces, Dasa, and DLR, is intended to improve crew situational awareness and assist in-flight planning and decision making. After describing CAMA's background philosophy and architecture (including situation information acquisition, interpretation and assessment, planning and crew interface functions), the paper went on to describe the parallel development of the software prototype Tactical Situation System. It consists of four main modules: Interpreter, Low-Altitude Flight Planner, Display, and Enhanced Flight Guidance Display (which provides computer generated 3-D imagery superimposed on a sensor output display). Demonstration and evaluation has included flight demonstration of the Enhanced Flight Guidance Display which – in answer to a question – Dr Schulte said had been useful in showing the difficulties of combining synthetic and sensor images.*

The paper "Sensor Fusion for Modern Fighter Aircraft", by Taubenburger and Ziegler of Dasa, GE, presented by Joseph Ziegler, used a beyond-visual-range scenario for illustration. Comparison of onboard radar, infrared and ESM sensor coverage (including on-board weapons' sensors) pointed up their advantages and disadvantages in terms of range and resolution and the potential for increased coverage by multi-aircraft cooperative sensor utilization via data links. The sensor fusion functions include kinematic correlation, identity fusion, threat assessment and sensor management, while implementation involves trade-offs between hardware availability, track continuity and accuracy, data bus loads, and independence of input data. The process sequence operates on input data at the sensor/data source level with associative and cost matrix analysis before fusion by Kalman filter and utilization. A typical architecture showed a data bus link between the sensor management and fusion system and independent input/outputs to sensors, fire control, and pilot controls/displays, retaining the capability for utilizing the output of the sensors directly and individually, or through the sensor fusion system. The discussion that followed highlighted the importance of improving quality – and presentation – of threat information to the pilot.

*** Footnote:** The Symposium Chairman, Mr Larry Ott mentioned plans for an MSP working group on distributed command and control for coordinated strike packages, for which this and other symposium papers were relevant.

SESSION VI: ROLE OF COMMERCIAL COMPONENTS

This final session was devoted entirely to papers on the use of COTS (Commercial Off-The-Shelf) components and related topics, a subject which had cropped up several times in other papers. The emphasis on COTS was a recognition that, at a time of diminishing defence expenditure, advanced avionics systems can only be made affordable by making use of the huge investments in commercial information and electronics technologies, and where possible, influencing its direction.

The first paper of the session, "Impact of COTS on Military Avionics Architectures", by Carbonell and Ostgaard of the Wright Laboratory, Wright-Patterson AFB, US, provided an overview from a User perspective. The paper was presented by Juan Carbonell, who started with a reminder of the 1994 "Best Commercial Practices" initiative of the US Secretary of Defense, William Perry, which was followed by a Wright Laboratory study in 1995 of the implications of using COTS hardware and software in avionics. He made the observation – unsurprising, though noteworthy – that "eliminating unnecessary constraints" on contractors offers major cost saving potential; particularly for necessarily non-commercial items such as sensors, which make up over half of avionics costs compared to the digital "core" area which accounts for only about a quarter. The main issues addressed in the paper included: packaging and the problem of military environments; obsolescence and its management; software, with particular reference to commercial standards and the implications of US DoD legal requirement to use only Ada as a high level language; testability and COTS inadequacies; throwaway modules as an economical alternative to diagnostic test and repair; and finally, system implications, with particular reference to open standards. The paper concluded by stressing the need for a flexible, systems approach to COTS and acknowledging the need to avoid overspecification and universal imposition of MIL-STD processes which, in the past, have militated against affordability.

The next paper, by Grasshof (Daimler Benz Aerospace) and Foerster (Daimler Benz Inter Services), GE, was concerned with a specific programme, related to the EUCLID and ASAAC modular avionics programmes referred to in earlier papers. Matthius Grasshof presented the paper, "An Approach Towards Integration of a Modular Core Avionics System Kernel", which described SYMS (SYstems Management Software) designed specifically for modular avionics application. The need for this special (Ada) software development, following an earlier experimental modular avionics

system using VMEbus hardware and a commercially available operating system, indicated some of the limitations of commercial systems for advanced avionics systems. SYMS has experimentally demonstrated the flexibility and reconfigurability required and its facility for integrating COTS or ROTS (Ruggedized Off The Shelf) systems and components. In reply to questions regarding additional software overheads and performance, the author referred to the next steps of the ongoing programme which will include further demonstration of real applications.

The next paper, "Low Level Flight Capability of a Future Military Transport Aircraft Based on Commercial Avionics" was by Kricke and Schäfer of Daimler Benz Aerospace Airbus, GE. It was presented by Dr Dieter Kricke, who began with a summary of flight guidance systems for commercial aircraft on which the military transport would be based. The basic elements of fly-by-wire, autoflight control, and flight management were described, followed by special military mission needs such as low-level segments and subsequent board-autonomous landings (that is, self-contained and unsupported by ground control systems), plus deviations from pre-planned routes in response to threats. Additional flight management functions include on-board flight profile re-planning, accomplished with special controls and displays (particularly a touch screen LCD for inputting way point data, and automatic 4-D flight path generation), special flight plan execution of landing windows etc., and low level flight guidance information by head up display. The discussion that followed centred on the special needs of military transports, such as the demands on flight control and propulsion response from dropping heavy loads.

Marlow Henne, of Sverdrup Technology, presented the final paper of the symposium – "Selecting a Software Developer in a Specification Free Acquisition Environment" by Henne and Kandel (University of South Florida), US. It directly addressed an important issue raised in the first paper of this session, that of managing programmes that are no longer subject to detailed government specification of the development processes. The USAF's Aeronautical Systems Center (ASC) has introduced Software Development Capability Evaluation (SDCE) as a formal approach to contractor selection. It recognises that past performance is not always a reliable guide and emphasises in-plant evaluation, with particular attention to selection of a review team. Six functional areas are considered in the evaluation: program management; systems engineering; software engineering; quality management and product control; organizational resources and program support; and finally, program specific technologies; with further subdivision into critical capability areas. Although the approach might appear somewhat bureaucratic, the author claimed the process had been shown to be effective, time efficient, *and fair*. It had also shown itself useful as a support tool during development, to identify strengths and weaknesses by "Red Team" reviews. The paper stimulated a good deal of discussion, much of it concerned with the wider application of the technique to other Services and within Industry. In answer to a question on measurement of SDCE effectiveness, the author reiterated the comments made in the paper on the value shown by 25 in-plant visits so far.

PANEL DISCUSSION: THE IMPACT OF ADVANCED ARCHITECTURES ON AFFORDABILITY

The Chairman, Larry Ott suggested by way of introduction three discussion topics – architectures, information management, and COTS – and made three related observations: firstly, that Military Users should take advantage of commercial hardware and software as a key driver towards affordability; secondly, that the cost reductions from open architectures should become practical as the technologies of data/signal communications networks were put in place; and thirdly, that dissemination, fusion and utilization of tactical information to improve situational awareness could simplify sensor requirements, though it might require more automation to limit crew workload to acceptable levels.

He noted a great deal of international recognition of the issues involved – for example: the introduction and retrofitting of open systems and the achievement of commonality across different aircraft types; COTS in relation to military needs, particularly in platform upgrades; the impact of open architectures on the Defence Industrial Base, such as new ways of doing business and changes in the roles of companies; and the questions of data integrity, real-time availability and crew acceptance in implementing "crew assistants".

Ross Edwards warned against fixing too quickly on any particular technology for implementing advanced avionics – such as SCI for example – which might risk early obsolescence. It was not enough to seize on a new technology or standard and produce a demonstrator: transparent systems were needed in order to avoid ripple effects of a single technology choice and to provide the desired flexibility and adaptability for growth and change. Terry Domae added that a simple software/hardware interface by itself was not enough: COTS implies the need to accept change and plan for limited life.

Dieter Kricke, offered a slightly different perspective. Experience in the last fifteen years showed that early technology decisions followed by system analysis through two or three layers, resulted in systems with built-in obsolescence. He called for a "paradigm change" to carry out system analysis *before* hardware selection. The need for new R&D approaches was supported by Jochen Potthaus, who commented that it was no longer appropriate for international programmes to be constructed around the division of hardware responsibilities. Experience had shown the value of

full-blown simulations *in advance of* procurement decisions.

Reed Morgan commented that discussion of avionics architectures focused too much on data processing, and he reminded the Symposium that most avionics expenditure was on sensors. There was a need to shift attention to adaptable digital signal processing – a new discipline requiring a wider breadth of interest. Ken Helps, UK (Chairman of Session V) remarked that the COTS approach might have a lot to learn from the automotive industry, where signal processing devices were expected to survive 8 to 10 years or more. Similarly, an open, Java-like software approach might be expected to provide much needed system transparency.

The big issue identified by C H Krueger, was the inevitable high cost of on-board avionics, whether in procurement or support. He cited the case of GPS receivers, available over the counter commercially for a few hundred dollars but costing half a million dollars for aircraft installations. The best way round the problem of high cost avionics was to "take it off the aircraft" as far as possible and instead use external data/information sources as proposed by Williams and Collier (paper in Session I).

John Niemela, US (Chairman of Session IVA) raised the question: what would be the process for re-qualifying highly integrated avionics suites, where a small change could affect the whole system? Reed Morgan made the further point that some of the implications of accepting de facto commercial standards – such as Fiberchannel which could fairly soon be superseded in the market place – were frightening. He also argued the case for field-programmable gate arrays that would enable software control drivers to be kept separate from the rest of the software – a POSIX-like concept that is perhaps two or three years away and might allow systems to "roll with the punches" of COTS changes. Ross Edwards pointed out that the ASAAC reloadable protocol answers that particular software problem, though the problem of an adaptable physical interface remains.

The discussion of COTS utilisation was rounded off by Ir Henk Timmens (Chairman of Sessions IIIA and IIIB) who advised caution. The costs of implementing COTS policy, and the possibility that incomplete and incoherent systems might result, may not become apparent for five or ten years.

The Round Table Discussion concluded with a general expression of concern on the ability of software development to keep up with hardware development, presenting a severe bottleneck on progress towards advanced avionics systems. It was also acknowledged that the issues of re-useability and transportability had not been as fully addressed in the Symposium as they might have been.

CONCLUDING REMARKS

This successful symposium covered a lot of ground, directly or indirectly relevant to the title and theme. If a slight reservation may be made, it is that military needs, research programmes, applications and technology were so interrelated in many papers as to produce some inevitable loss of coherence in the symposium as a whole. For example, several papers could just as easily have been assigned to other sessions as the ones in which they appeared. However, this did not detract from the overall value and interest of the symposium which covered the subject of advanced aerospace mission systems architectures in width and depth.

The overall impression that emerged was of a major impact on future military capabilities that will result from developments taking place on both sides of the Atlantic in signal and data processing/communications and related areas of advanced information technology. These advanced technologies hold out the promise of highly integrated mission systems that will be much more adaptable, fault tolerant and affordable than present systems. The fact that much of the hardware and software technology is commercially inspired makes the drive towards COTS utilization at once more readily attainable and at the same time a source of concern in two respects: firstly, the requirements for advanced avionics in key areas remain in advance of commercial developments; while paradoxically, the extended life span of military systems can leave mature systems with hardware and software standards that may be obsolete and no longer supported in the market place. Suggestions for overcoming these concerns included closer involvement by defence avionics companies with commercial electronics companies (with advantages to both parties) and more frequent pre-planned upgrades (with user benefits of more up-to-date and effective avionics).

The response of most delegates to the papers presented, and to the symposium as a whole, was positive, as indicated by replies to the questionnaire circulated to attendees. Three out of five replies gave the symposium an overall score of between 80% (significant) and 100% (extremely valuable) – that is, the return exceeded or far exceeded the individual's contribution. Virtually all the remainder considered it to be generally relevant or important, scoring between 50% and 80%. There was disappointment from a few specialists at the lack of depth in papers covering their subjects, though this was to be expected in an Unclassified symposium. However, most of those attending thought the symposium was well balanced, informative and valuable.

Keynote Address

Requirements for Advanced Avionics Systems Architectures

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1. INTRODUCTION

It is indeed an honor and a privilege for me to be given the opportunity to provide this opening address to such a distinguished audience from NATO, National Governments, industry and research institutions at this NATO-wide symposium on "Advanced Architectures for Aerospace Mission Systems". I hope that all of us will benefit from the exchange of ideas and information to be presented here.

This technology-oriented symposium with emphasis on advances in advanced architectures for aerospace mission systems design and development will give us the opportunity to review current and future trends of technology, to study the use of advanced avionics architecture systems and design, the advantages in relation to current systems and to focus attention on the cooperation and exchange of information and ideas between the operations and research and development establishments.

My message today will focus on the requirements for advanced avionics systems, architectures, interoperability, standardization and the implications for the way equipment is currently contracted for and built.

2. MAIN BODY

Performance, availability and costs of airborne weapon systems are increasingly being determined by the avionics system, its sensor systems, embedded computing systems and associated software.

Fast evolving capabilities of sensors and real-time computing systems enable the fulfilment of new and far reaching requirements with respect to system effectiveness and system availability and to implement new functionalities such as:

- sensor fusion, which means the consolidated presentation of terrain, threats, obstacles and targets for an integrated tactical situation display ("Situation Awareness")
- automatic target detection and target classification,
- on board threat analysis,
- reduction of crew workload through automation of cockpit functions,
- comprehensive presentation of the overall situation (including the collection and assessment of current operating conditions of the weapon system through intelligent onboard test and diagnosis systems,
- in-flight information exchange by jam resistant data links throughout the own and friendly forces,
- cooperative tactics,
- increase in the mission performance and mission success probability by resource - sharing and reconfiguration of mission critical functions,
- surveillance and reconnaissance, in particular detection, identification and tracking of highly mobile targets.

These new capabilities are of especial importance since the number and variety of airborne systems are decreasing while at the same time one weapon system has to perform different roles and missions.

Reductions in the defense budgets require that these improvements need to be made with minimum development and procurement costs while at the same time reductions manpower require that the availability of the weapon systems needs to be provided with less maintenance and lower personnel demands.

This requirement, combined with changing operational scenarios which demand an essentially higher degree of flexibility, mobility and interoperability for airborne weapon systems within the alliance, require:

- a high degree of test- and diagnosis capability up to the module level without external test means,
- reduced (two level) maintenance concept,
- improvements in Turn-around Time and Mean Time To Repair (MTTR),
- lower and simplified spares provisioning,
- high degree of standardization and compatibility with other weapon systems within the alliance through reduction of the variety of avionic modules,

taking into account the existing requirement of 30 days or 150 hours maintenance free operation during crisis and wartime scenarios.

Furthermore Advanced Architectures must support for those system engineering aspects which are related to changing or updating the system, which means in essence that open system qualities must be achieved. Open system qualities are defined as those features that are supported by the system architecture, which reduce the effort required for changing, enhancing or upgrading the systems.

Present NATO airborne systems incorporate avionics consisting of many different types of electronic assemblies and subassemblies that have been designed in accordance with application and manufacturer specifications There is little use of commonality in the implementation of assemblies or in the components used in various systems apart from a few rare exceptions. Consequently aircraft systems are constructed from a large number of different components all of which require maintenance.

Paper presented at the AGARD MSP Symposium on "Advanced Architectures for Aerospace Mission Systems", held in Istanbul, Turkey, 14-17 October 1996, and published in CP-581.

This variety of components generates high operational costs and problems when upgrading or adapting systems. It also means that the scope for improvement of reliability is limited due to the costs of pursuing this for all the individual items.

Further, since commonality is not exploited in the development of components, this results in high development, acquisition and operational costs as well as unsatisfactory system efficiency and availability.

These problems are aggravated for future systems where systems with greater complexity are required with higher degrees of automation and special functions for, in some cases, only brief mission phases.

In addition to the hardware, the system software components will both increase in quantity and become increasingly more complex. It is well known that the costs of software development and subsequent maintenance form a major part of total system costs. This is not helped by having to create software to different application standards for every application due to lack of commonality in hardware.

To attempt to meet the objectives of reduced Life Cycle Costs, improved mission availability and increased technical and operational interoperability there needs to be a move away from conventional avionic systems. The direction of this move is towards integrated avionics systems.

Integrated avionics means designing the elements or components to work together as part of a total system, i.e. taking a total system design approach from the start. The basis of the physical integration approach is the exploitation of commonality. To achieve this, common modular building blocks and their interfaces must be clearly defined together with rules governing their use in a way which does not constrain their use through lack of flexibility. The integrated avionic elements or building blocks can comprise both hardware and software modules.

Integration can also be applied during a total system approach to the avionic functions. This functional integration requires determination of the way in which individual avionic functions are managed within a system by grouping similar functions into "integration areas" (such as CNI or EW suites).

The process by which integrated avionics are generated should be clearly distinguished from that of conventional avionics (or systems) integration. The latter is used to mean the process of bringing together elements designed as separate sub-systems often with little regard for a total system approach.

In conclusion, the above objectives will be met by a move towards a modular integrated avionics architecture.

The preceding discussion introduced the concept of integrated avionics using hardware and software building blocks. However, the integrated avionics system will be constructed from both common and non-common elements. The non-common elements will include sensor front ends, effectors and actuators, and software which is application specific, all of which have to carry out very specific functions. This may extend to include other hardware or software for which insufficient contribution to cost or operational advantages have been demonstrated through the application of commonality.

The above-mentioned problem areas can only be solved by the consequent application of advanced avionics architectures (Integrated Modular Avionics, "IMA"). Standardized hardware and software modules will be used which can be applied over a full variety of weapon systems and which can be interconnected in such a way that a fault tolerant, reconfigurable system architecture can be implemented.

While the external interfaces and characteristics of the modules will be left to the implementer, so allowing the maximum use to be made of the latest technological developments, particularly those available via Commercial of the Shelf Components (COTS).

The different avionic modules will be interconnected via standardised interfaces by advanced databusses and networks with high data rates and will jointly provide mission-oriented functions (e.g. navigation, identification, fire control). The operational reliability will be guaranteed by multiple and redundant use of similar modules. General purpose module such as data-, signal and graphics processors, transmitters/receivers, power supplies and interfaces will be integrated in a core and combined with modules for special functions such as special purpose signal processors. The use of the same modules will result in large quantities during production and thus reduce procurement costs tremendously. The amount of maintenance will be reduced by simple exchange of modules at the flight line.

The advantages of advanced avionics architectures with respect to selected operational properties can be described as follows:

- **System Survivability:**

  Consolidated situation presentation and signature reduction through sensor fusion; real time data exchange with cooperating forces, integrated presentation of the information in the cockpit.

- **System Availability:**

  From the present average of a number of hours to up to 30 days or 150 flying hours maintenance free operation, introduction of a two level maintenance concept (only exchange of faulty components) with reduce requirements for personnel (numbers, training).

- **Multimission Capability:**

  Simplified adaptation of the weapon system in the in service phase through additional hardware modules and operational software.

- **Mission Success Probability:**

  Guaranteed mission capability of the avionics system after failure of single components due to functional redundancy through multiple available modules, graceful degradation of the system.

- **Mission Effectiveness:**

  Improved target recognition and identification in real time through sensor fusion and tactical decision-aiding functions.

- **Interoperability and Deployment:**

  Improved mission and logistic support due to fewer standardized module types which are cross-serviceable and improved maintenance. Improved interoperability from an operational point of view.

- **Life Cycle Cost:**

  Reduced procurement costs, simplified spares provisioning through smaller number of module types. Savings through reduced servicing requirements.

Only advanced avionics architectures will provide the simultaneous availability of all these advantages in a weapon system.

However, with these advantages come many implications for the way equipment is currently contracted for and built. The integrated system design increases enormously both the system complexity and the potential for interactions between sub-systems. At the same time it blurs the traditional lines of responsibility that exist in the industry and it will, therefore,

require a very careful and systematic design approach if integrated systems are to be put together successfully. To implement such highly integrated systems, very close collaboration between systems engineers from different avionic, airframe and software suppliers will be required.

3. CONCLUSIONS

In summary, we in NATO need to ensure that our important technical achievements in the field of "Advanced Architectures for Aerospace Mission Systems" find their way into improved avionic equipment for combat forces in order to enhance our defense capabilities. This is after all our overall objective. We must improve the cooperation and exchange of information among the nations of the alliance. We must move toward cooperative development projects that will lead to affordable equipment for NATO while at the same time reducing the proliferation of systems and the associated problems of interoperability and high logistic support cost. The dialogue between user and experts from government, academia and industries must be continuous because we need your knowledge and assistance to improve today's systems to counter tomorrow's threat.

Symposia like this can be of great value in promoting this process and all of you are encouraged to address yourselves to the problems which I have briefly mentioned. I am extremely pleased to be the speaker for the opening address and feel privileged to recognize the efforts made in organizing this symposium. I would like to take this opportunity to personally and on behalf of the German Ministry of Defense, express special thanks to AGARD, and all those who have contributed in organizing what promises to be a very productive week.

Advanced Avionics Architectures - Where are We Going?

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1. ABSTRACT

We will explore the question of where avionics architectures are today, considering the Joint Strike Fighter and the evolution of open system approaches from the PAVE PACE and PAVE PILLAR programs of the 1980's. The recent work extends today's notions of a unified software and hardware approach to core processing and a common interconnect between architectural elements, not only to sensor or signal processing, but toward the apertures themselves and the system development environment. We shall take a broad view of the problem that includes RF electronics, interconnect, operating systems and application software development, processing hardware, and the system development environment itself.

The architectural extensions discussed here are made in the context of the basic long term technology trends of more digital sensor processing and preprocessing, higher performance analog-to-digital converters, lightwave technology for both signal distribution and routing, and software structures that reduce development expense, while increasing the supportability and portability of applications software. Future RF electronics modules will be waveform independent and support multifunction apertures in a given spectrum for a selected bandwidth, with a strong impact on affordability since the RF sensors and their associated electronics correspond to some 70 percent of avionics fly-away cost.

We will show how decoupling the explicit interactions of various system elements simplifies development and system integration by removing unwanted design dependencies and providing upgrade paths for cost effective technology insertion, with minimum system breakage. These techniques will be used to implement the principles of modularity, scale up, and ability to upgrade that have become part of the today's open system approaches and will be even more important in the future as the opposite poles of capability and affordability govern both new systems and upgrades. A coherent integrated architecture that promises more affordable development, implementation, and support is presented as the answer to the question, *"Where are we going?"*

2. AVIONICS SENSORS

Avionics providing affordability and low risk is the expectation in RF architectures. This is specifically true on current programs in which a 50 percent reduction in avionics cost over the previous architectures is the goal. In the digital domain, processing architectures can take advantage of commercial developments - that is not the case in the RF domain.

Today's inventoried sensors use federated approaches that provided single function operation with minimal integration with other sensors. This approach makes upgrades difficult and costly while locking the government into the hardware developer. Adding new technologies requires redesigns to the hardware and software due to the tight coupling of the architecture. Overcoming these issues requires the development of a highly integrated concept with the attributes of piecewise integration, minimal module types, near-aperature digitization, adaptable to platform and mission changes, and independence of the software from hardware implementation. Hence, an open system architecture with a framework for defining building block elements with well defined interfaces and top-level functionality is needed. Our philosophy is to define interfaces between functions that support three or four generations of growth before a redesign is required.

The integration approach taken by several programs, extending from PAVE PILLAR and PAVE PACE, looks to architectures with common hardware and software interfaces for a low cost solution. Current programs are pursuing this goal by developing common receiver modules that can be utilized by multiple functions. These programs are moving the industry in the right direction, but offer only a small step toward the higher levels of integration required to see a major payoff in cost, weight, and performance. Higher levels of integration will be achieved through the migration of the digital interface outward toward the aperture, thereby placing the traditional analog signal processing completely in the digital domain.

As the key technologies, such as the Delta/Sigma ($\Delta\Sigma$) analog-to-digital converters (ADC) increase in performance, the network interconnect and the signal processing resources must be capable of transferring and operating on higher data rates for broader bandwidths.

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Future network interconnects will be based on photonic technology that are transparent to communication protocols. Current wavelength division multiplexing (WDM) techniques being developed by commercial industry provide in excess of 3 Thz of bandwidth per fiberoptic link which could simplify the wiring in aircraft and move the processing closer to the aperature. Issues that require futher attention include the areas of maintainability in military environment and connectors.

3. ARCHITECTURE

3.1 Today's Architecture

Today's architectures can be most easily described in terms of their characteristics. We have moved from federated to at least partially integrated structures, but commonality among functional modules is still a goal rather than a reality. Many fielded architectures have been modified or adapted to include 1980's digital technology. Backplanes and interconnect networks are separate entities.

The use of application specific integrated circuits is commonplace, although the total number of circuits employed remains very small, usually a few thousand units at best. Lightwave technology has been introduced but only initially exploited.

The advantages of building to standard interfaces is recognized, but existing efforts have been concentrated on military oriented standards which have achieved little or no following in the commercial marketplace. There is still considerable debate as to whether commercial standards can satisfy military requirements for realtime, low latency operation, fault detection, and fault tolerance.

Software is still structured around realtime executives or highly customized kernels. Most application software is still highly coupled to the execution software in fielded systems. Techniques for application reuse are primitive or have yet to demonstrate scale-up. Operational flight programs, taken together, usually represent less than a million lines of code. These flight programs are written in variety of languages including JOVIAL, CMS-2, and Ada.

Affordability has improved on a per function basis, but the increase in functional requirements has resulted in an overall increase in flyaway costs. Today's situation is marginal at best.

3.2 Impact of Needs, Technology, and Trends

By considering what is really important in an architecture we establish a context for our projections of where the combination of needs, technology, and evolving ideas are likely to take us.

Affordability stands at the top of the list of presently perceived needs. Closely related are scale up, technology insertion, reuse of existing software, and the flexibility of new software. The cost of the RF subsystem presently dominates avionics system costs, while software costs are rising rapidly and becoming a major life cycle cost component. Tomorrow's architecture must be implementation independent at least one layer away from the point of insertion of system upgrades.

Tomorrow's architecture will use description languages to allow virtual prototyping of system tradeoffs, while preserving requirements tractability. Effective approaches to fault isolation and reconfiguration will also be necessary. Similarly, development support, integration, and maintenance environments are highly desirable.

Everything changes! Remember when a VHSIC-implemented MIL-STD-1750B computer was the answer to all present and anticipated needs? The parallel interconnect bus and Futurebus+ were successive answers for a suitable follow-on MIL-STD-1553B. There is a new addition to the major processor families -- Intel's x86, Motorola's PowerPC, and Sun Microsystem's SPARC -- at least every two years. Whether we have entered a period of rapidly changing interconnect approaches -- Scalable Coherent Interface (SCI), Serial Express, Fibre Channel, and Asynchronous Transfer Mode (ATM) - is not so clear.

If we are to avoid the significant development costs of military-only solutions, we must solve the problems of a continuing supply of "soon to be out of production" solutions, or architect systems that allow the insertion of new technology with minimum disruption to supported functions. If the inability to introduce new technology is a constraint imposed by the architecture, then tight coupling between elements of the architecture is certainly one of the causes.

Tight versus loose coupling has typically been a performance driven argument. Shared memory versus message passing is a classic example. Loose coupling may introduce a degree of independence among elements, but the extra communication and corresponding delays and processing overhead decreases performance, perhaps in critical areas.

It is important to remember that previous solutions sought to optimize the hardware implementation, given the technology available at a point in time, and to make the solution common to as many platforms as possible to provide economies of scale. But a realistic consideration of the scale of commercial versus military requirements leads to the inescapable conclusion that all the military requirements we could aggregate through commonality have no appreciable effect on price or delivery, when compared to commercial demands for the same part numbers.

Tight coupling was the most efficient solution, but with all the elements of a system highly interdependent, upgrades were costly and difficult. Major portions of the previous implementation were abandoned during upgrades.

Has today's technology reached the point where we are processing capability rich and can now concentrate on formulating more desirable architectures based on considerations of scale up, adaptability, ability to upgrade, and life cycle affordability? We appear to be data processing rich -- in terms of raw capability. Perhaps we will be signal processing rich after the turn of the century.

The more complex an architecture the more expensive, the more difficult to upgrade, and the greater the disruption with the insertion of new technology. Global shared memory approaches and complex cross-bar-like switches may be fine for small systems, but as soon as we attempt to scale them the complexity increases exponentially to the number of system elements. Conscious efforts at keeping a simple, unified approach are needed.

Integrated architectures have been introduced to promote resource sharing and flexibility for the future. They complement digital processing trends and the increasing implementation of functionality in software. Proponents of older federated approaches argue that integrated architectures are more difficult to integrate because essential modularity and separation of functions is lost to supposed resource optimization. There is a question of the applicability of digital -- in portions of the RF subsystem -- and the software architecture approach. Integrated architectures, properly defined, will continue to be a major source of avionics cost reduction.

We define an architecture in terms of interfaces to establish modularity, foster competitive approaches to functional implementation, and to simplify integration. Minimizing and simplifying the number of interfaces simplifies integration. A principle advantage of a unified interconnect network is that it minimizes the number of interconnects or network interfaces. Well-defined interfaces are the means by which newer, more economic technology insertion is achieved. Well-defined interfaces also promote competition by allowing different suppliers, both present and future, to compete effectively for upgrade and support opportunities.

The avionics system interconnect is a prime example of the need for effective standards and also presently one of the most frustrating areas of architecture definition. While a unified, or single interconnect protocol simplifies integration, it makes the selection of the protocol that much more important.

We have experienced a long period of interconnect "stability" in which MIL-STD-1553B dominated military systems while ethernet and VME were the principle network and backplane standards, respectively. In the commercial world, we have entered a period of flux in which new standards such as the parallel interface (PI) bus, FutureBus+, Fibre Channel, and the Scalable Coherent Interface (SCI), Asynchronous Transfer Mode (ATM), and Serial Express are appearing or disappearing at roughly the product cycle time of a microprocessor family member (we see no connection, incidentally). The question is whether that is a temporary instability, while the next major standard emerges, or a prolonged period of rapidly changing standards. The answer may be crucial to the success of open architectures.

We assume that the military approach will follow the commercial approach with due consideration of realtime and latency needs as well as environment. It is hazardous to speculate on the right solution until we get an adjudication of Serial Express in the commercial marketplace. Presently, commercial designs seem to be moving to VME64 backplanes and 100 Base T ethernet for local area networking. At this point we doubt that ATM will catch on at the desktop. Serial Express is being considered for small work group interconnect applications.

Previous systems have been requirements driven. This has led to worst case designs for worst case scenarios -- possibly with penalties for ordinary operation. We are entering a period where we will be requirements compliant, rather than requirements driven. By virtue of improved scalability and the recognition that future technology, if affordable, will upgrade performance at regular intervals. Commercial components, bought to manufacturer's part numbers, in standard or optional volume production packaging will dictate the performance of these upgrades. Affordability has become the predominant driver in the procurement of new military avionics.

As programmable hardware solutions become less and less expensive as a function of improvements in microelectronics technology, applications software increases in relative importance and cost in the system solution. Yesterday's custom hardware is becoming today's firmware and field programmable gate arrays, and will become tomorrow's software. This means that efficient methods of writing independent applications to a common application interface that facilitate integration will become even more important in developing, supporting, and upgrading avionics systems.

The principal method of decoupling applications software from the execution of hardware is through a layered operating system. The application programming interface to the operating system is critical to the efficient development of application code, particularly during system integration. Thus, we find that the software architecture is perhaps the most important element of the system architecture.

4. SOFTWARE

The complexity of avionics software systems have changed dramatically. Over the past few decades, avionics software has grown from a few thousand bytes running on a dedicated processor to be close to a million lines of source code. Functionality has grown from simple navigation and simple sensor processing to very complex cooperative attack, imaging, and information management techniques.

Beyond the increased complexity, software must meet the procurement challenges of the future just like the core processing hardware and interconnection networks. Standards, software reuse, information architecture offer some interesting possibilities to address some of the life cycle cost questions.

We will try to understand where software is going by trying to first understand the attributes of today's software, and what is necessary to meet the perceived needs for tomorrow.

4.1 Today's Software

Probably the largest advance in the past few years in the area of software is the introduction and wide spread application of sound software management. Given the growth in the size and complexity of systems, today's software organizations focus on sound software management. Collection of metrics, training, process refinement, reproducibility, and to a lesser extent supported by software tools.

Software management is clearly an important, but some organizations singularly focus on software processes -- achieving that capability maturity model level five. Sound software management processes are not the whole story, but a combination of product and process innovation is necessary.

There has been minimal software technology innovation in the past few decades as compared to process innovation. Clearly, some software technologies like fuzzy logic, distributed systems techniques, genetic algorithms, and rate monotonic analysis have made their way into some systems. However, this does not compare to the innovation seen in process, processors, or even avionics algorithms (e.g., multi-target tracking).

Software languages have changed from assembly to JOVIAL to Ada, but software development techniques have remained mostly unchanged, and consists of basic embedded software development environments with customized debuggers and debugging interfaces. Much of the debugging is dependent on having the real target systems available to each integrator/developer. However, initial integration and target emulation are helping to minimize target integration and test requirements.

Design methods have not changed for fielded system; structured design has been practiced for the past few decades with software reuse being an after thought. Object oriented design is slowly creeping into systems, and investment in reusable and maintainable software appears to be accepted.

Constructive simulation, man-in-the-loop flight simulators, ground based flight trainers, and operational flight programs currently all implement the same functions using common requirements with different software organizations and software baselines. This can lead to a divergence in system behavior and "throw away" simulation software.

Today's avionics software is tightly coupled with the underlying hardware. Device driver implementation in application code is a common occurrence, and many codes are dependent on the underlying byte ordering of the processor. Custom extensions for the compiler are also common. For example, compiler extensions for mapping timers or other special hardware dependent functions to application functions are expected by most avionics organizations. The setting of explicit processor priorities and making explicit calls to fault and memory management code is also common. All these things make today's avionics software less reusable and therefore less valuable for future systems.

Today's avionics software utilize custom executives and operating systems to preserve processor resources. This condition is rapidly changing with the exponential increases in microprocessor speeds, and the advances in operating system technology. Today, standards bodies like the Institute of Electronic and Electrical Engineering (IEEE) and the Society of Automotive Engineering's Avionics Systems Division (SAE-ASD) are standardizing the application programming interfaces (API) to realtime operating systems.

Signal processing software currently is achieved using high order language for back-end operations (e.g., tracking, fusion, sensor mode, etc.) and assembly language for front-end functions (e.g., waveform timing control, basic digital filtering, etc.). Technology programs, such as Rapid Application Specific Signal Processing (RASSP), have explored the concept of visual programming of the digital filtering pipelines. In this paradigm, common digital filtering operations are represented as blocks, and the visual tool glues the blocks together. When the program is compiled, the glue code is automatically generated, and the blocks are simply library calls to predefined operations implemented by the tool or chip vendor in assembly code. This provides for quick application coding, and efficient runtime performance.

4.2 What's Important in Software

Avionics applications of the future must exhibit some important characteristics to meet the needs and

expectations of open systems. The following discussion lists some of these avionics application characteristics.

Avionics application programs should be portable. Avionics applications should not be dependent on architecture (processor, memory, inter-process communication, device driver codes, tasking priority, security, and fault tolerance attributes). Specifically, avionics applications should not directly incorporate pieces of device drivers, explicit priority operations, explicit security requests, and explicit fault tolerances requests from within its code.

Portability also means that application software will be insulated from changes in the processor. Applications must be functionally independent of the processor (e.g., produce the same results exclusive of timing dependent features), and applications must be performance independent of the processor (e.g., produce the same results inclusive of temporal events). In other words, applications should have the ability to be moved from system to system (without change) and have the application behave identically.

The application software must be predictably engineered and specified to meet both the functional and performance specifications so that application software does not require change when hardware changes.

Avionics applications should be modular. Applications should be built for expansion, and should not incorporate policy decisions into the code. Policy decisions should be encoded in table form (e.g., waveform priority data should be an input to the multi-function radio system). This approach would allow new transmission priorities to be implemented without changing the underlying radio system. Changes would only be necessary if new waveform types were introduced.

Avionics applications should be evolvable. Application development should allow a continuous transition from initial conception to flight deployment and maintenance. Applications should not be treated as "throw away" between each phase of an aircraft program.

Avionics applications should easily incorporate new algorithmic codes from emerging technology programs (e.g., fusion architecture algorithms). This implies that the environments expected in these technology program should be supported in the avionics.

Avionics applications should be constructed as multiple cooperative tasks with priorities, and exchange data with priorities. Creating an avionics system from many smaller tasks with discrete priorities supports the previous goal of modularity, and allows the software to minimize the effects of priority inversions.

A given avionics applications should not be able to interfere with another application. For instance, one application should not be able to write into another application's private memory space. Applications must have a measure of system integrity and security implicit in their environment. This is typically not enforced in a standard Ada environment where the avionics consists of a single program and program memory space.

Avionics applications should not be able to act upon incomplete, incoherent, or in-flux data. This is an application design goal for real-time systems, and applies to both shared memory and message passing systems.

Avionics applications should be capable of being implemented in multiple languages. There are several cases in an avionics system where use of other languages may be necessary (e.g., signal or image processing). Thus, applications should have the ability to make heterogeneous language calls (C++, Assembly, domain specific language). Clearly, assembly coding is not desired because of its lack of portability, but may be necessary in some limited cases to meet latency requirements.

5. AN INTEGRATED SYSTEM APPROACH

To achieve the goals outlined for avionics software characteristics, an integrated system's approach is necessary. Core processors, software, and sensors cannot individually achieve the benefits of open systems, but together they can change the way avionics is done.

5.1 Integrated System Development

Evolutionary system development approaches are needed to carry avionics work products from requirements concept through support without loosing information. Requirements methods/tools have direct relationships to system architecture methods/tools, which in turn links directly to software architecture and software design elements. The maintenance of these relationships through manual or automated means is important. The challenge here is not establishing these relationships for the first time, but maintaining them over decades of system maintenance in a useful form that allows fundamental requirements to change and have minimal impact across the system.

For example, a landing beacon system specified using today's methods map requirements to many system architectural components (e.g., communications, displays, etc.) that eventually trace to software architecture objects and so on. Thus, the impact of removing such a system requirement causes a system wide ripple effect in an integrated architecture, but has minimal impact in older "steam gauge" era architectures. This ripple effect is primarily caused by the outdated process and methods that have direct dependencies to the older "build it once" architectural methods.

If the processes and methods were integrated and focused on incremental development, the ripple effect would be minimized. Methods that promote object creation throughout the life cycle help to minimize this effect by creating distinct parts that can be assembled. These parts must be manageable from end to end in the development life cycle, but this only solves half of the problem. The other half of this problem is the glue between the objects. Intra-object contracts and relationships need to be established and maintained: interfaces, priorities, fault management, etc. Defining the volatility of interface points must be tempered by the technology half-life of the components on each side of the interface. Some interfaces choices are very important at a given time because of technology's rate of change (e.g., custom operating system interface versus standard operating system interface).

This vertical application approach parallels the federated approach to systems. Instead of the federated pieces being the traditional avionics subsystems (e.g., navigation, mission management, etc.), the pieces are objects that result from system architecture analysis (a form of domain analysis). This process can be carried out iteratively, with change impact decreasing as successive layers of the system are defined. This results in fine grained objects that can be reused. Further, a fully integrated avionics object can be created and delivered independently.

In terms of process, this vertical object breakdown structure supports incremental refinement of the system by providing clear interfaces. This allows for independent hosted development of each of the objects for functional capability, and to some extent a capability for hosted integration. Key to both hosted development and hosted integration/test is a prototyping and integration environment. Final platform integration, meeting timing and specific device requirements, must be done on the target processor.

5.2 Prototyping and Integration

Another dimension to a system approach to avionics is the system prototyping and integration environment. This environment provides the surrounding test fixtures to accomplish both unit and integration test in both a hosted environment and final bench testing on the target. The prototyping interfaces also include the necessary models to mimic components of the system for basic unit test.

This prototyping and integration support environment includes man-in-the-loop test fixtures (cockpit controls and display), sensor domain simulators (infrared, visual, radio frequency, etc.), threat simulators, vehicle simulators, core processing simulators (if necessary), and interconnect simulation (if necessary). This support environment enables initial integration testing of the system objects as soon as possible.

The prototyping interfaces are modeled after the initial system decomposition, and are extensions to the interface descriptions. With reasonable fidelity models for each system object, basic unit testing is possible using a newly developed system object, a set of object models, and the support environment. Functionality can be evaluated on a host computer with all parts of the system represented, and subjective attributes can be evaluated through man-in-the-loop interaction. Priorities and security constraints specified during the system architecture are used by each model to set actual tasking priority and access limitations during prototyping and integration.

This type of prototyping and integration environment allows the avionics functionality to be evaluated in a high productivity environment (on desktop assets). This evaluation during this phase is done for proper behavior, not for efficient resource utilization. This prototyping and integration environment does not address resource allocation issues, but must provide the specific timeline information required for resource estimation. Analysis tools are used to estimate processor, memory, and network usage.

5.3 Resource Analysis

Resource analysis balances the timeline requirements produced by the integration environment against the various architecture configurations to arrive at estimated resource utilization.

The architectural objects produced by the system analysis are mapped to elements in an architecture under evaluation. Thus, specific functionality is mapped to specific hardware for the purposes of loading and traffic analysis. The timeline information from the prototyping environment forms the basis for the loading profile used to stimulate each portion of the system. Peak loading can be determined, and the architecture configuration modified to optimize the number of processors or networks.

Each processing domain has its own unique analysis tools, so signal processing, data processing, and network analysis do not share analysis tools. Reducing and correlating the output data from these tools requires some simple data management utilities.

6. CONCLUSIONS

Integrated architectures will become the rule rather than the exception for new systems or major upgrades. Integration will proceed rapidly in core processing, much more slowly in the RF electronics.

The awareness of problems in technology insertion and upgrades of tightly coupled system will become better

understood. Simularly, layering of systems will become better understood. Layering of system software and eventually RF hardware will be used to reduce the system impact of technology insertion. Reduced performance due to the decoupling techniques will be mitigated by the more capable hardware available through newer technology implementations. There will be an emphasis on scalability for solving increased capability needs and providing requirements-compliant solutions. Modularity, the need for which is already well-established, will be based on commercial standards whose interfaces are in wide-spread use with implementations in volume production. We will order components to a manufacturer's part number based on compliance with an industry benchmark or standard.

In the interest of reducing complexity and simplifying integration there will be an emphasis on building systems out of sets of simple structures that are easily programmed to meet a mission need.

We will have to let the commercial marketplace sort out interconnect solutions for next generation equipment before tying ourselves to a particular standard. This may take two or three years and considerable patience. We must also consider the possibilities of dealing with realtime and high priority data at the upper layers of the protocol stack, rather than insisting on physical level solutions that the commercial marketplace has little interest in. Custom approaches for the military will have a strong appeal from a requirements viewpoint, but they will be increasingly unaffordable.

Perhaps the greatest changes will come in software. Software architecture will become the dominating factor in avionics architecture. The operating system, the system development environment, and provisions for software rehosting and reuse will be among the most important considerations. The layering that makes application software independent of the execution hardware will be accomplished in the operating system. The application programming interface is critical to application independence, portability, and software reuse.

Change is also coming rapidly to the RF area. There will be modularity based on generic interfaces that will have implementation independence, yet align with overall technology trends. A handicap here is the lack of standards and the limited success of previous efforts have proved too dependent on the digital implementation technology. Digital implementations will have a strong effect on these interfaces as programmable digital approaches emerge for functions in the 200 Mhz to 2 Ghz spectrum.

We have stressed the need for architecture independence of hardware and software and hence the need for technology independence in future architectures. But architectures must also consider major technology trends. Is this an oxymoron? We don't think so.

Independence of hardware and software deals with the independence of hardware and software implementations. Major technology trends refer to the fundamental way in which we approach solutions: analog versus digital, hardware versus software, or the interconnect bandwidth. The architectural notions presented here are based on assumptions about the future paths of technology trends.

We think there is a strong trend toward digitization of previously analog functions. This will have a major effect on approaches to RF functions, most immediately on communications, navigation, and identification. Custom hardware will be replaced by programmable hardware with strongly increasing capability per dollar benefits. Much of the functionality of future avionics systems will be defined in software and the code size of operational flight programs will increase dramatically. Finally, we think that light wave signal distribution will replace coaxial cable signal distribution with corresponding benefits in reduced weight and increased bandwidth. The latter will allow distributed integrated system to evolve.

Information - The Warfighter's Edge: The Joint Strike Fighter (JSF) and System-of-Systems (SoS)

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• *Background*

It has been proven throughout history that information can provide the warfighter with an edge needed to win the battle and ultimately the war. For this reason we have seen, over time, increasing investments in data collection and dissemination systems. Today, these systems include national, theater, and tactical-level capabilities that provide a variety of data types. Current examples of theater collection systems include AWACS, E-2C, JSTARS, Rivet Joint, Guardrail, EP-3E, ES-3A, and Predator, Global Hawk, and Darkstar UAVs. Tactical collection systems include wingman, other flight groups, Forward Air Controllers (FACs), and Hunter, Pioneer, and Gnat UAVs. These systems provide electronic intelligence (ELINT), imagery intelligence (IMINT), and radar intelligence (RADINT). Only recently has this data been made available to the warfighter in near-real-time (NRT). This data, when appropriately processed and converted to information, can be used by the warfighter for situation awareness and targeting to enhance survivability and lethality.

Taken together, and properly orchestrated, these off-board collectors form the support structure for Intelligence, Surveillance, and Reconnaissance (ISR). The addition of a Command and Control (C^2) function is required to complete the off-board portion of a SoS construct. Effective C^2 is based upon authority combined with the ISR information needed for decisions on appropriate target weapon pairing. These decisions must support both the normal Air Tasking Order (ATO) cycle generation and NRT C^2 for time-critical-targeting (TCT).

The USAF Scientific Advisory Board's (SAB) *New World Vistas* study introduces the concept of "Global Awareness" as critical for the 21st century. "Global Awareness" is defined as the "affordable means to derive appropriate information about one or more places of interest after a delay which is short enough to satisfy operational needs." Various other ISR agencies have also placed an emphasis on support military operations (SMO). For example, the Defense Advanced Research Projects Agency (DARPA) has placed "comprehensive battlefield awareness" as first among its top ten military priorities. The objective of these efforts is to improve the effectiveness of the warfighter, while leveraging the ISR assets toward cost reductions of new lethal tactical systems.

• *Problem*

It is precisely the escalating cost of tactical systems that has placed affordability as a top priority in the development of the JSF weapon system. The JSF Program Office (JSF/PO) has adopted four "pillars" that focus the efforts of the potential weapon system contractors (WSC's). These pillars are:

- **Affordability**
- **Lethality**
- **Survivability**
- **Supportability**

Ongoing studies by the WSCs surround and support a balanced look at these pillars with the figure of merit being life-cycle cost (LCC).

A premise adopted by the JSF program is that by judicious choices in the sources for tactical information, reductions in on-board avionics can be achieved. The questions confronting the WSCs is how to gain these cost cuts without reducing the Warfighter's capability or transferring the cost from the warfighter community to the ISR community. These questions must first be confronted by a proper understanding of the

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trade-space. Figure 1 shows that the trade-space has four elements: (1) the assets that can be brought to bear by the ISR community, (2) the structure of the C^4 architecture, (3) the components of the on-board avionics suite and (4) the concept of operations (CONOPs) under which the war fighting objectives will be addressed.

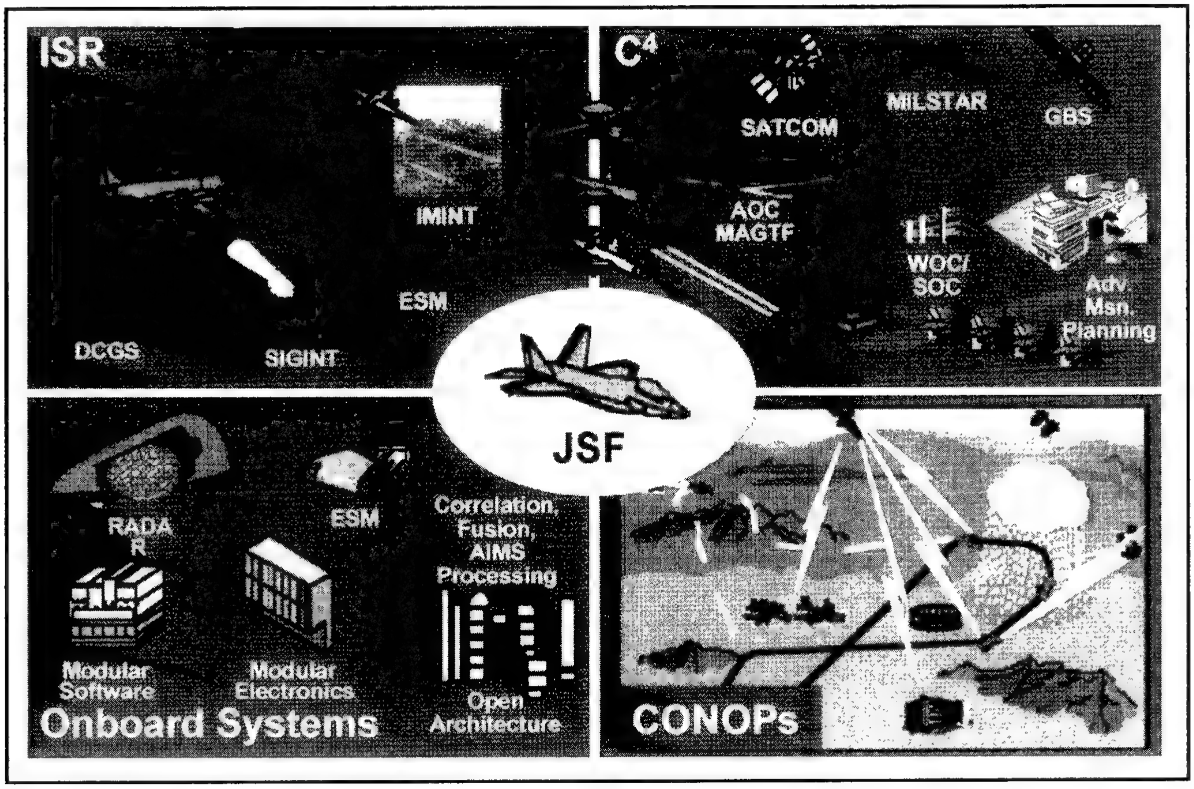

Figure 1 –Components of the SoS Trade Space

It is true that the JSF program does not have total control of all the elements involved in the trades, but, as stated earlier, the support communities are posturing their planning to provide SMO. For this reason, JSF program interaction with the various agencies involved have proven to be very cooperative. More flexibility exists in performing the trades than might first be assumed. The interchange to date has provide a clear definition of what legacy assets are available but a somewhat less clear view of future assets. Indigenous to the US department of defense (DoD) is the process called the Five Year Development Plan (FYDP). DoD uses the FYDP to show Congress goals and plans for weapon and support systems development. The problem is that funding usually will not provide for all the developments that DoD requests. Therefore, the C^4ISR support systems available to the JSF in circa 2010 can only be postulated.

This ambiguity, while complicating the process, does not preclude *some* trades. Certainly, some existing systems will continue to be in operation by that time, while other new high priority systems will almost certainly receive funding.

• *Potential*

To understand the potential support that can be expected from the ISR community, an examination of legacy and high-priority assets have led to broad categorizations of ELINT and SIGINT. From an aircraft perspective the use of off-board data also falls into two broad categories: (1) situation awareness (SA), which can be related to the pillar of survivability and (2) targeting, which can be related to the pillar of lethality. Figure 2 shows the most probable relationships between these functions. ELINT data has limitations for targeting because of issues on *accuracy*. As a result, ELINT may only be used for targeting in the case of weapons with the appropriate seeker. Similarly, IMINT is rarely used for SA because of *latency*. Efforts are underway within the ISR establishment to reduce latency that will have some impact on this situation. Figure 2 also shows where command and control (C^2) fits in the overall concept of operations.

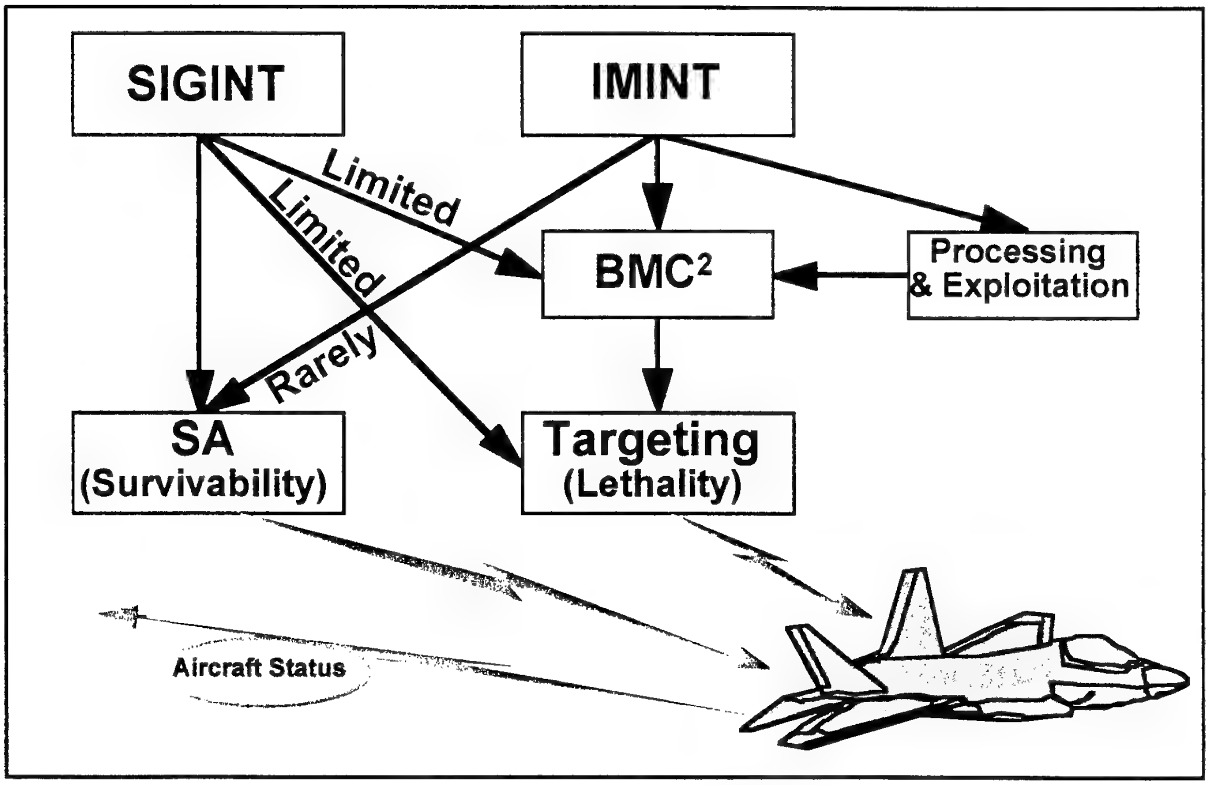

Figure 2 – Off-board Data Supports Lethality & Survivability

Another observation on the use of off-board data is depicted in Figure 3, where a forward line of troops (FLOT)-centric and an aircraft-centric view of the current ISR are shown. The FLOT-centric view shows that the *availability* of ISR support diminishes with aircraft penetration beyond the FLOT. This situation presents a need to the JSF for autonomous operation during deep penetration into enemy territory. Similarly, the aircraft-centric case shows that utility of ISR support decreases as range decreases with respect to the JSF based upon *latency* or *timeliness* of the ISR support. Hence, two issues that must be addressed with ISR support is availability and latency or

timeliness. The good news is that these issues *are* being addressed by the ISR community.

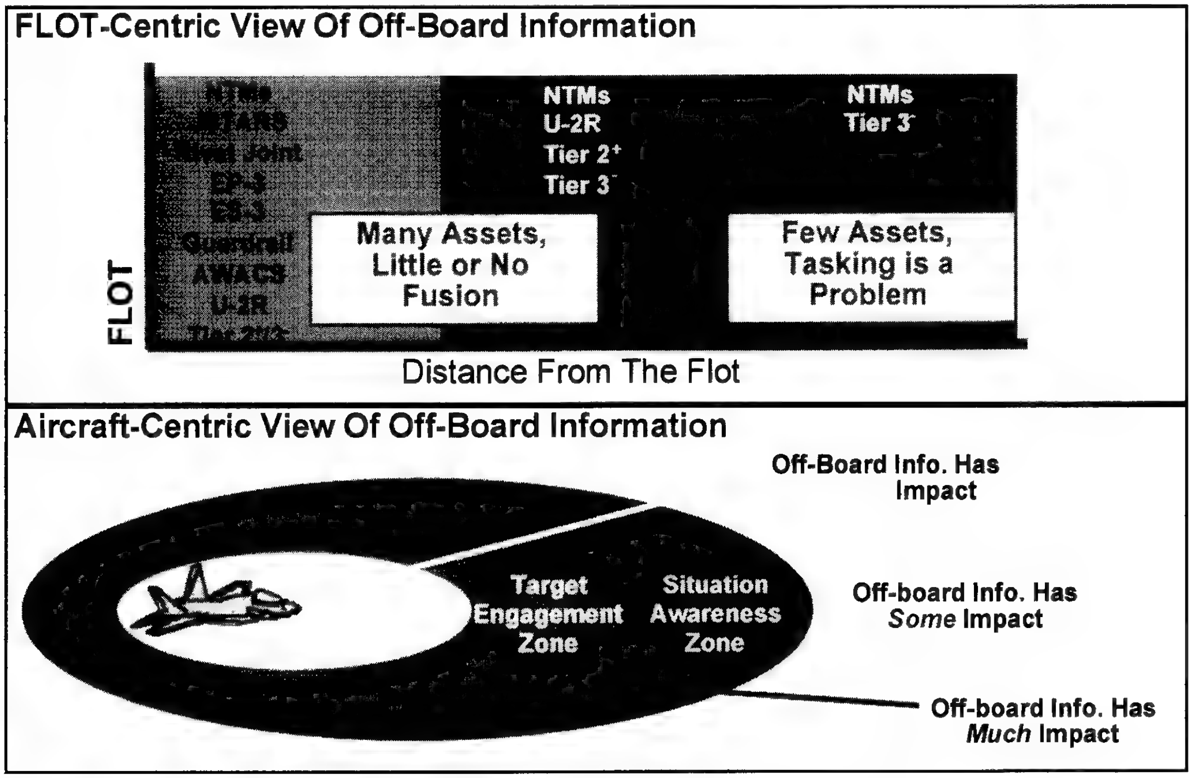

Figure 3 – Problem: Asset Availability vs. Range

It is clear that the cost of on-board avionics is directly correlated with the level of off-board support from the ISR assets in the SoS context. Figure 4 indicates that a *balanced* approach must be formulated to *affordably* meet the needs of the JSF warfighter. The figure highlights several of the issues relevant to achieving the desired balance. On the avionics functions side, the power-aperture-product (PAP) of the radar, the sensitivity of the electronics support measures (ESM), the number and types of communications links and the amount of on-board processing must be traded against the off-board support in the areas of availability and latency of target and threat updates, which may require the re-tasking of ISR assets, and overall battle space awareness. The figure also introduces the concept of cooperative operations between aircraft for synergistic effect. These operations might include cooperative ranging, cooperative jamming or sensor sharing.

Figure 5 shows what a vision of the JSF battlefield might look like in circa 2010 with the emphasis on existing ISR assets to keep the figure unclassified. However, it is clear from examination of the figure that there are many potential ISR sources with a variety of data types. Currently, these assets have a variety of datalinks and protocols that present connectivity problems. However, the Joint Chiefs of Staff (JCS) within the DoD have chosen Link-16 as the primary tactical data dissemination datalink of the future for purposes of standardization both within the

US military and coalition forces. Current plans also call for distributed common ground stations (DCGS) for processing of all types of data from the various collection assets. The DCGS supports both the Joint Intelligence Center (JIC) and the C^2 nodes within the theater. The most likely scenario is that SA data will be broadcast via the Global Broadcast Service (GBS) and that NRT targeting data will arrive at the JSF via the C^2 nodes along with tasking/re-tasking command authority.

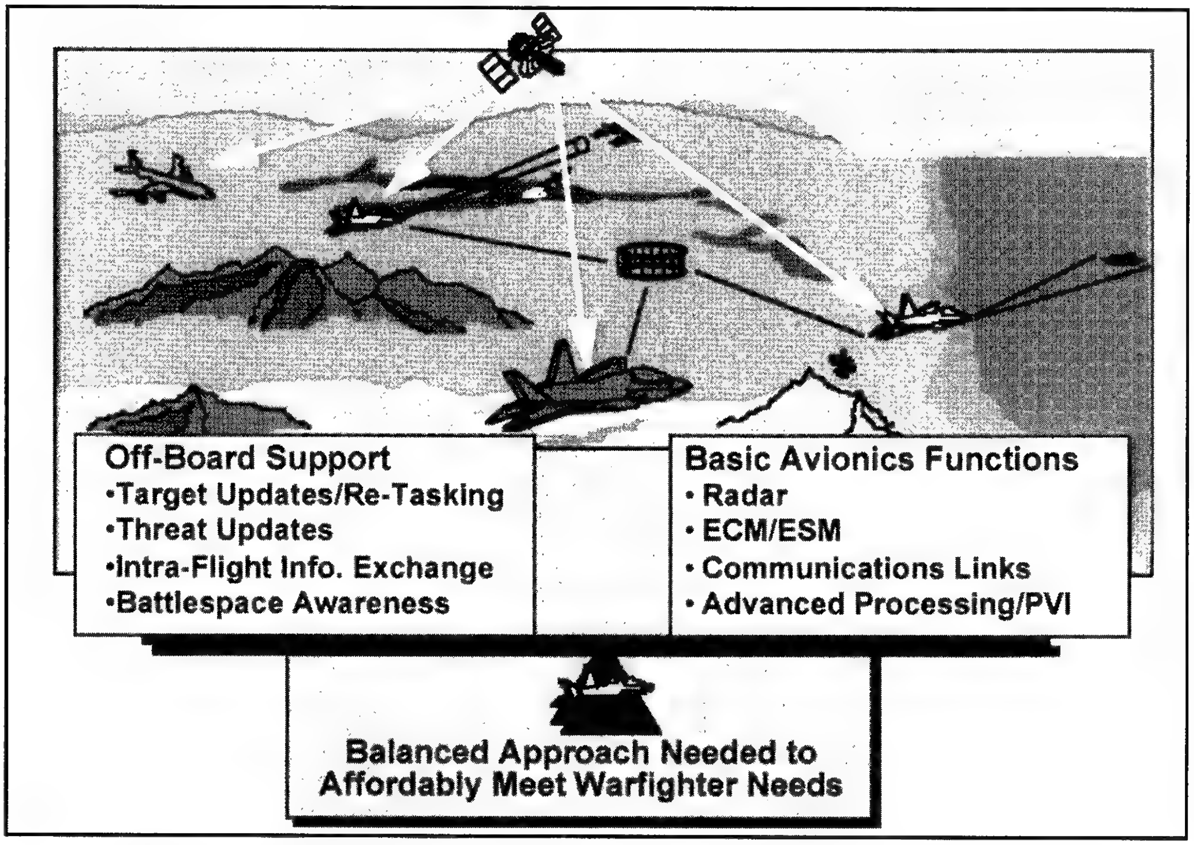

Figure 4 – Avionics Cost/Capability Varies With Off-board Support Level

From an engineering perspective this SoS architecture is the natural extension to the integration process that WSCs have historically been performing during the development of new weapon systems. Figure 6 depicts how the various levels of connectivity can be done in a new SoS paradigm. The JSF on-board avionics architecture must be capable of this expansion to include off-board "busses." The most likely condition is that these off-board busses will perform three functions: (1) make broadcast intelligence available to JSF, (2) support the command and control linkages and (3) support cooperative operation between platforms, either like- or diverse types.

Today, there are many datalink networks which support a partial implementation of the desired connectivity, e.g., TADIL-A, TADIL-B, TADIL-C, etc. The shortfall is that these existing links provide networks for C^2 platforms, but not many fighter-attack-

bomber aircraft. The DoD is making a concerted effort to minimize the number of dissimilar datalinks and standardize on Link-16/TADIL-J data networks for the dissemination of this information through a long-term migration plan. The plan calls for the retrofit of Link-16 on almost all legacy platforms, including fighter-attack-bomber aircraft, with a life span of more than a few years. This choice also provides interoperability with several coalition forces.

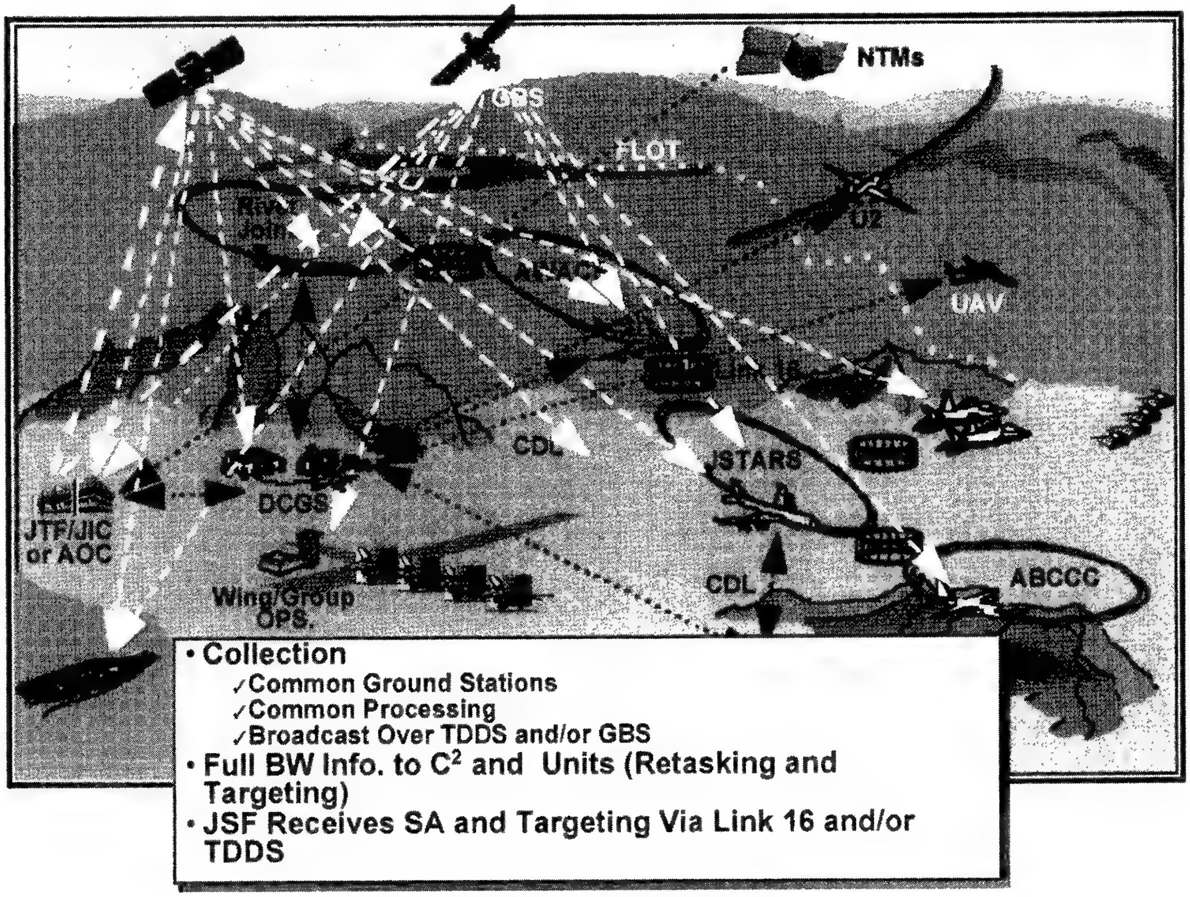

Figure 5 –Emerging JSF Battlefield Vision

This dissemination architecture challenge can be met by either of two concepts: off-board processing with subsequent dissemination or dissemination followed by a primary challenge for the WSCs in developing the JSF is to leverage the off-board portion of on-board processing. While off-board processing and dissemination might be preferable, legacy off-board systems have driven the JSF requirement toward on-board data processing. The reality is that both on-board and off-board processing will occur with dissimilar functions for that processing. The net result is the evolution of a SoS paradigm which drives the need for an advanced information management system (AIMS) on the JSF. AIMS then becomes an enhanced man/machine interface which is needed to enable the pilot to deal effectively with off-board and on-board data. AIMS

will transform this data into information and determine information relevance to current mission task. Advanced information management concepts such as information policy hypothesis development, evaluation, and execution are currently being developed for the JSF. This technology will increase the Signal-to-Noise-Ratio (SNR) of the man/machine interface. In the context of information, signal is the system declaration of tactically relevant information. By contrast, noise is the system declaration of irrelevant information. AIMS combined with SoS will provide the JSF pilot with the desired information advantage over the adversary.

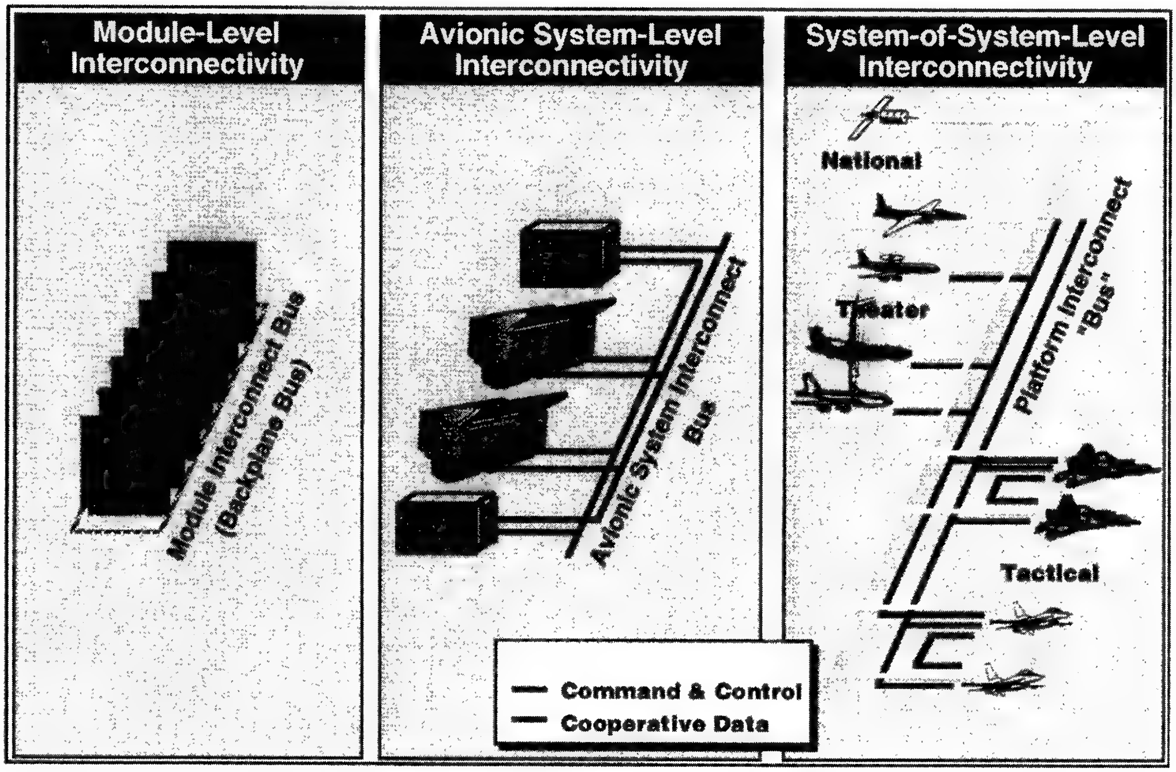

Figure 6 – SoS From an Engineering Point-of-View

Figure 7 shows a potential JSF functional avionics architecture that could embody the AIMS concept. AIMS is shown pictorially by the Core Data Fusion and Core Mission Management elements. Fire Control, Navigation and Fault Management are not new concepts but do have new functionality within the AIMS concept, e.g. failure of an on-board sensor can place a higher dependence upon off-board support and might allow the mission to proceed with off-board or wingman targeting and/or re-tasking to a different objective

A preliminary study conducted by Lockheed-Martin and called the On-board/Off-board Information Fusion and Management Study determined that the total data that might be available to the JSF would likely be overwhelming to the pilot and developed the concept of *information management policies*. These *policies* control the information shown

to the pilot at any given instant of time and are a sophisticated extension to the common "declutter" display feature of many of today's tactical aircraft. Policies are defined during pre-mission planning and transferred to the aircraft by the data transfer unit (DTU). These information policies are sensitive to mission phase and tactical situation, e.g., there are class policies (fighter, bomber, SAM, etc.), geometric policies (range and angle), interaction policies (fighter on intercept course to ownship, etc.), mixed policies (combinations of other policies), etc. study included an implementation of the concept in a mission simulation and was reviewed by pilots from the US Air Force, Navy and Marines. Ongoing studies and planned demonstrations are scheduled to explore the efficacy of the constituent components of this SoS/AIMS concept as will be shown later in Figure 8.

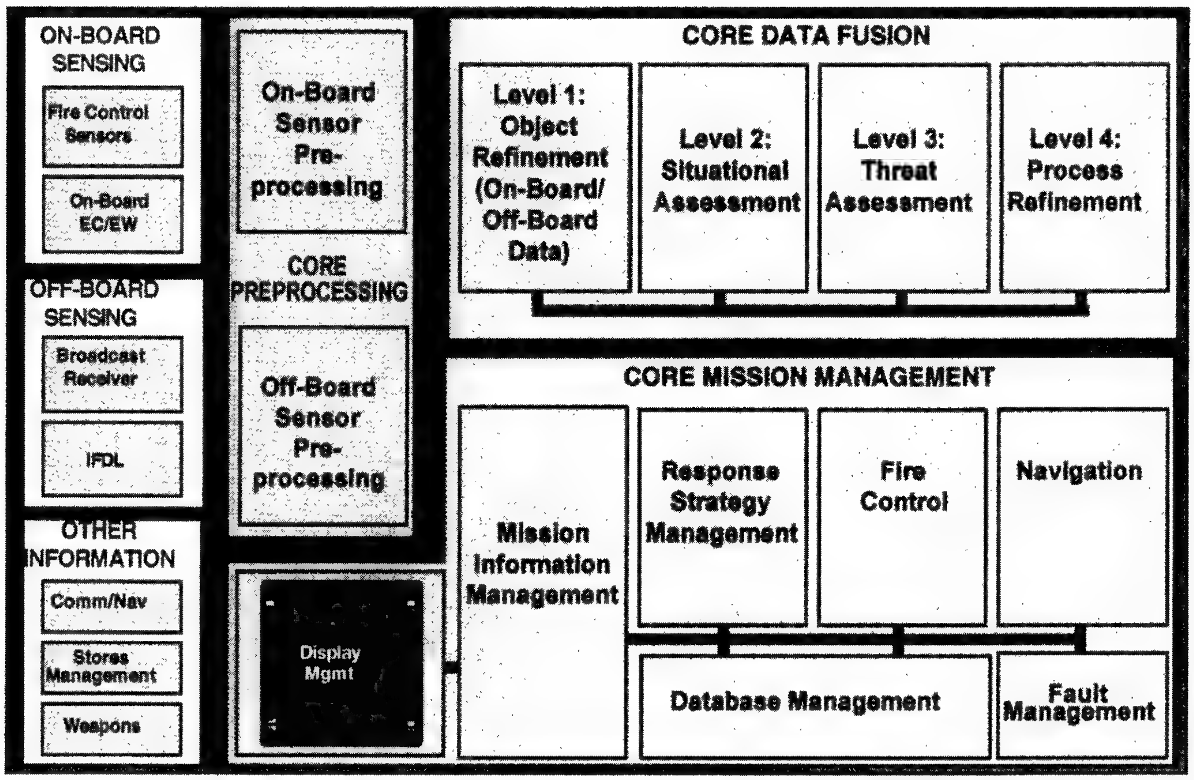

Figure 7 – Potential JSF Architecture Supporting SoS & NRT Targeting

• *Process*

The foregoing paragraphs have discussed the problem and the potential solutions posed by the SoS paradigm without defining a process to achieve desired goals. During the on-going Concept Definition Phase, the JSF/PO, via a Force Process Team (FPT) and Operational Advisory Group (OAG), has defined a top-level process to determine the JSF/SoS requirements. The product of this process is annual Joint Interim Requirements Documents (JIRDs) that focus on different aspects of JSF requirements. Current plans call for the SoS attributes to be defined in 1997 via JIRD III with SoS requirements to

be defined in 1998 with JIRD IV and final validation of SoS requirements to occur in 1999 resulting in the final Joint Operational Requirements Document (JORD).

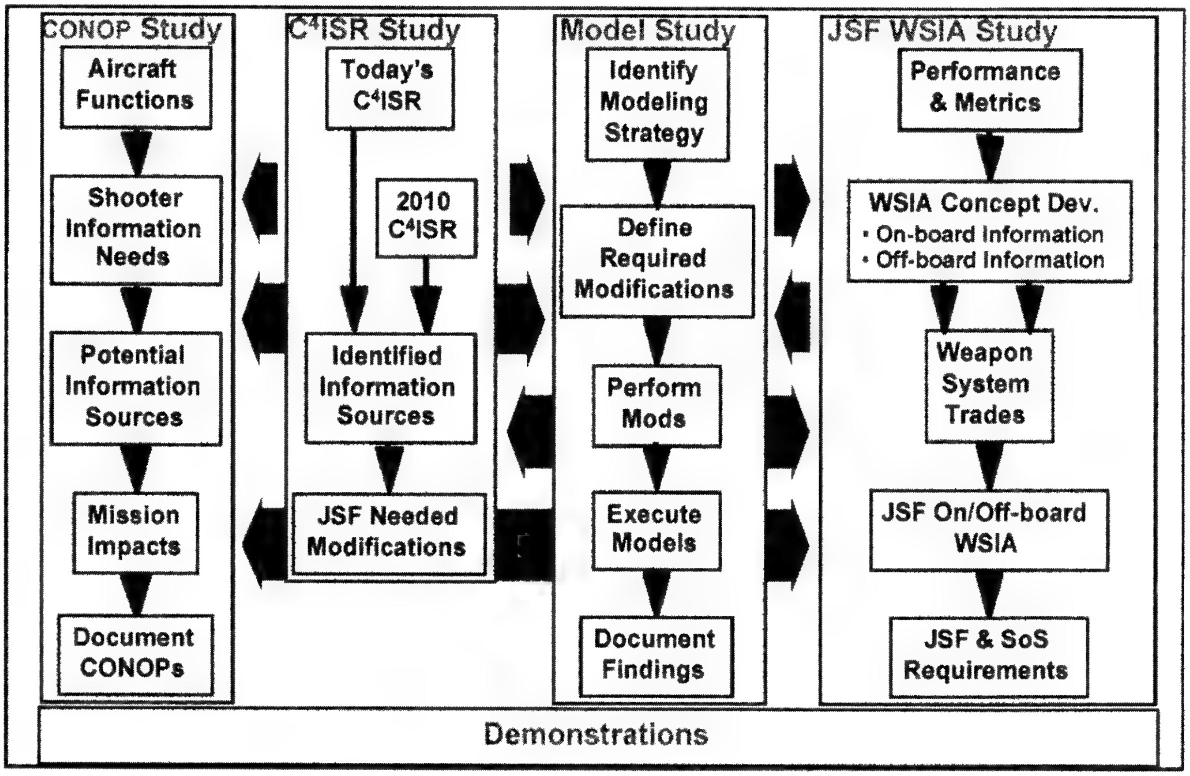

Figure 8 – SoS Trade Study Plans

Underneath this top-level process, several study plans are being developed that look at various needs as shown in Figure 8. The CONOPs study defines and matures the CONOPs element of the trade space shown in Figure 1. The C^4ISR study will build upon existing study results and be updated interactively as the ISR community plans for asset development solidify. Additionally, the results of JSF trades will influence C^4ISR planning to provide developments better suited to JSF needs. The model study addresses short-falls in current operational analysis models relative to incorporation of off-board and/or fusion influences. These models are then used to determine the cost-effectiveness of various CONOPs in the SoS paradigm. Finally, the JSF Weapon System Information Architecture (WSIA) study provides the "bottom line" on LCC for the various CONOPs. It is obvious that each of these studies interact with each other as indicated by the underlying arrows in Figure 8.

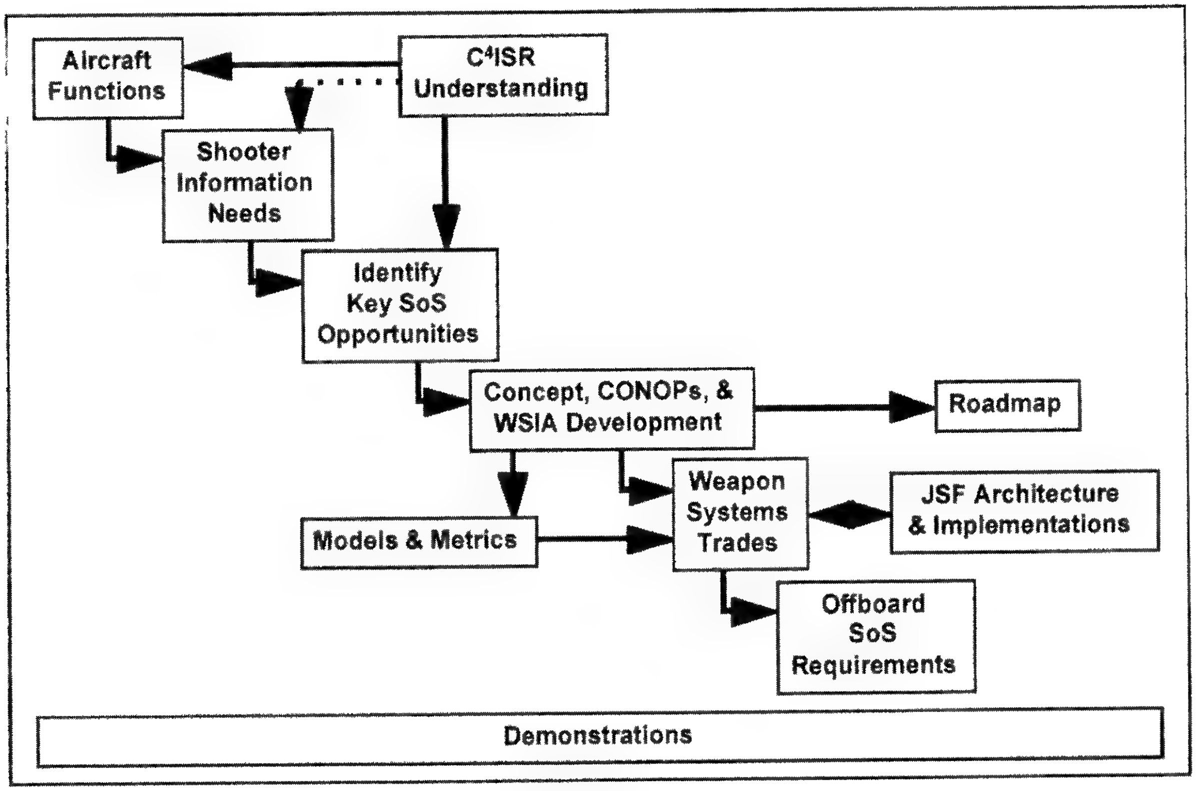

Figure 9 – SoS Requirements Process

Figure 9 shows the flow-down of requirements process that precipitates the trade studies indicated in Figure 8 and gives a context for studies in the overall JSF Strategy-to-Task-to-Technology (S-T-T) process. Both Figure 8 and Figure 9 indicate that the studies are supported by demonstrations to reduce the risk to the JSF program at Engineering and Manufacturing Development (E&MD). Some of the risk reduction demonstrations may be accomplished by high-fidelity simulations (referred to as the Virtual Strike Warfare Environment, VSWE, and/or Virtual Avionics Prototypes, VAPs, depending upon context) of the SoS concepts, while others may be attained by "brass-board" hardware coupled with the simulations or actual laboratory or flight tests. It is clear from Figure 9 that metrics will have a valuable part in the trade study process. The JSF Force Process Team (FPT) will determine these metrics as part of the S-T-T process. The proof of the SoS concept will be shown in real-world military exercises, e.g. Red Flag, Green Flag, or Joint Warfare Interoperability Demonstrations (JWID). All these efforts are directed toward the goal of the JSF program which is to achieve a "low-risk" system design prior to entry into E&MD. The process outlined in Figure 9 is ongoing, will continue throughout the upcoming JSF Concept Demonstration Phase (CDP) and will ultimately define the SoS attributes and requirements for the JSF JORD at the beginning of the 21st century.

• *Conclusion*

Complete autonomous mission capability for tactical aircraft is no longer affordable nor necessary in view of the SoS concept. The

JSF will rely upon national, theater, and tactical-level ISR to provide long-range target detection, location, and identification. On-board systems will employ cues from the off-board collectors but will still be required to provide targeting and weapon employment capability as a result of latency and accuracy issues with ISR collectors. However, the resulting JSF on-board sensors will be much less complex in terms of power-aperture product, aperture complexity and/or system sensitivity: the current cost drivers in avionics. Total weapon system performance will be maintained through correlation and fusion of off-board information with on-board sensor data. In effect, off-board data, correlation, and fusion technology will enable a smaller and less complex on-board sensor system to perform like that of a much higher performance/cost system. Use of wingman data will allow on-board systems to be designed for less severe simultaneous mode capabilities. Lower cost, non-interferometer, apertures on multiple aircraft will be managed to provide highly accurate range and bearing data. The implementation of a SoS concept will enable an affordable JSF which can be procured in large enough numbers to replace end-of-life aircraft for the US and NATO allies.

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COTS Joins the Military

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1.0 SUMMARY

The complexity of today's military system has caused the priority of *affordability* to rise to an unprecedented level among system requirements. An increasing number of government and defense industry leaders are relying on *commercial off-the-shelf* (COTS) products with the associated *economies of scale* and use of *non-developmental items* (NDI) to meet this requirement.

The affordability benefits of COTS and NDI for military systems are subject to several other factors. For example, as the need for products capable of operating in a hostile military environment increases, the number of products and vendors meeting these requirements decreases. In addition, military systems, which traditionally have been expected to survive for long periods of time, are subjected to two commercial phenomena that occur simultaneously – product prices decrease over time while technology provides an increase in product performance. The latter factor results in a dichotomy summarized as *parts obsolescence.*

This paper identifies additional military system issues and current commercial trends and postulates how these trends can be used to meet affordability requirements. The latter includes illustrated use of open system standards combined with *pre-planned product improvement (P^3I).*

2.0 AFFORDABILITY – AN INTERNATIONAL PROBLEM

The leaders of North Atlantic Treaty Organization (NATO) countries are responsible not only for the security of their countries and for strengthening the defense posture of NATO as a whole but also for the financial welfare of their people. The latter responsibility has led to a decline in military budgets and has resulted in defense system affordability problems for all NATO countries. To meet this responsibility, NATO Advisory Group for Aerospace Research & Development (AGARD) members and NATO defense leaders are actively pursuing a total mission system architecture approach that includes continuous system upgrade through technical improvements and the potential use of cost-competitive commercial off-the-shelf (COTS) equipment.

2.1 Premise

The theme for the sixth symposium sponsored by the AGARD Mission System Panel (MSP) describes past avionics systems as "stand-alone, dedicated suites [developed] to perform a single function such as [electronic warfare], fire control, communications, etc." Utilization of unique resources and functions for each of the dedicated suites contributes to higher initial nonrecurring as well as life cycle costs. Examples include the initial cost of fault tolerance (e.g., component redundancy) and life cycle costs for sparing, documentation, training, etc. The symposium's theme encourages research and development that will enable use of robust architectures – architectures that utilize common digital modules, common software, shared radio frequency (RF) and electro-optical (EO) apertures, and standard hardware and software interfaces, i.e., commodities that stimulate commercial investment for profits other than from military sales. An increasing number of government and defense industry leaders are relying on commercial investment to create commodities capable of meeting defense system requirements. These commodities have the potential to become non-developmental items (NDIs) for the military and hence reduce nonrecurring system costs. Today's NDIs generally fit into one of the following three categories:

- Commercial off-the-shelf (COTS)
- Rugged off-the-shelf (ROTS)
- Military off-the-shelf (MOTS).

2.2 Economy of Scale

The design and development cost of NDIs in general and COTS in particular is amortized across the quantity of marketable components. The amortization results in the economy of scale, i.e., as the quantity of sales for a specific item increases, the cost of each item decreases.

Unfortunately, commercial demands usually drive the design of COTS products. Subsequently, as illustrated in Figure 1, changes required to meet hostile environments result in fewer vendors, the need for fewer items, and a subsequent increase in cost.

For military systems to gain from the economy of scale, the defense industry must contribute to the design of new products, i.e., merge military requirements into COTS products (eliminate the need for differences between COTS, ROTS, and MOTS).

3.0 FUNDAMENTAL ISSUES

Aerospace mission systems are complex collections of platform subsystems and functionality. Historically, each dedicated aerospace mission system suite consists of unique equipment and associated algorithms. The complexity of integrating unique equipment adds to system development time as well as to initial system design, procurement, and life cycle costs.

Paper presented at the AGARD MSP Symposium on "Advanced Architectures for Aerospace Mission Systems", held in Istanbul, Turkey, 14-17 October 1996, and published in CP-581.

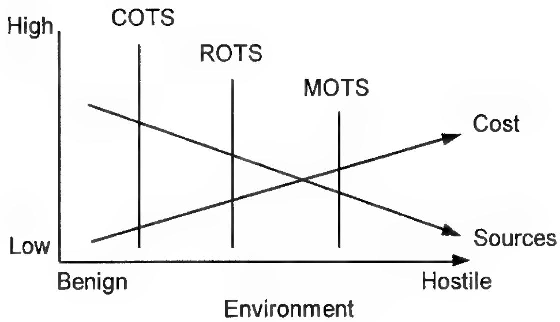

Figure 1. Military System NDIs and the Economy of Scale

Affordability dictates that new defense system programs seek a balance between the initial nonrecurring/procurement costs and life cycle costs as illustrated in Figure 2. For peacetime military systems, this cost is distributed over a relatively long period of time, i.e., a new strike fighter can easily take 10 (or more) years from conception to first article delivery and remain in service in excess of 20 years.

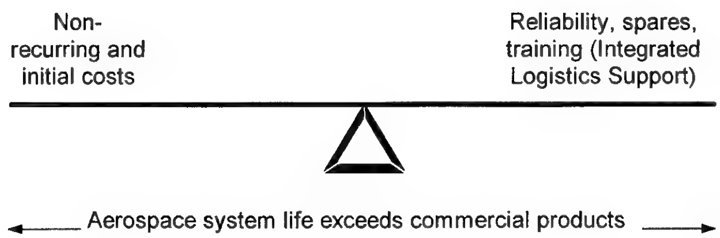

Figure 2. Product Life Cycle is Typically Longer for Defense Systems

Because of the quantities involved in the development of commercial products, nonrecurring costs can be amortized over a shorter period of time. The end product is subsequently subjected to the two simultaneously occurring commercial electronic industry phenomena illustrated in Figure 3. The result is a decrease in product prices while technology provides an increase in product performance. Both contribute to a shorter product life cycle, which, from a traditional military perspective, creates a dichotomy referred to as parts obsolescence.

Commercial industry has taken advantage of this phenomena by creating a commodity market. A commodity market enables the incremental development and integration of systems using open system components. Examples of commercial open system components include the personal computer (PC), PC clones, local area network (LAN) protocol/adapters (e.g., Ethernet adapters), system interface buses/adapters (e.g., Small Computer System Interface (SCSI) and Peripheral Component Interconnect (PCI) adapters), communication protocol/stacks (e.g., Transmission Control Protocol/Internet Protocol (TCP/IP) adapters) and shrink-wrapped software. The open system concept encourages profit-motivated competition which results in a variety of COTS products, the use of new technology, an increase in the number of suppliers, and ultimately, a decrease in product costs.

3.1 A New Role for System Developers

For the development of new military avionics systems the challenge is how to gain the performance and affordability advantages of COTS without creating a parts obsolescence problem that is significantly more severe than before. When system developers move toward a greater demand for COTS and a smaller demand for components from military suppliers, the few remaining military suppliers will disappear and system developers will become responsible for the problem of parts availability. This is a significant responsibility since the functionality, quality, and reliability previously guaranteed by military suppliers will be gone. Unfortunately, this will not be a responsibility that will be assumed by COTS suppliers. This void in the quality chain must be filled in order to guarantee the delivery of systems that are supportable, maintainable, and reliable.

This new role for system developers will require a much closer relationship with COTS suppliers. Without this relationship, a system developer will not be successful in placing military requirements on commercial suppliers or reacting to product changes that result from changes in commercial markets.

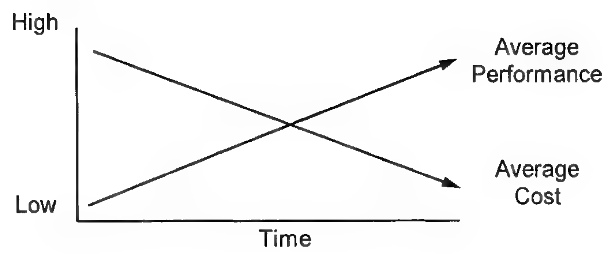

Figure 3. A Product of COTS Economics – Parts Obsolescence

In order to benefit from the advantages of commercial markets, the system developer must understand these commercial markets and therefore the motivation behind the suppliers into these markets. Only then will military system developers be able to anticipate changes that will be made due to trends in processing architectures, memory designs, interconnect protocols, bandwidths, supply voltages, etc. Additionally, the system developer must take responsibility for understanding the capability and therefore the limitations of commercial components in military environments. By accepting these responsibilities, the system developer can plan for the insertion of new COTS technology as the commercial markets evolve rather than suffer the cost and schedule impacts of unanticipated and inevitable changes in COTS components.

3.2 COTS Mandates Continual Technology Insertion

Military systems have life cycles that are significantly longer than the typical 12- to 18-month life cycle for COTS products. Most commercial PC suppliers release new configurations every 3 to 4 months and these configurations are usually supported for 12 to 18 months. For military systems, a system usually needs to be supportable for 20 years or more. Unfortunately, supporting a 20-plus-year system with elements that will be obsolete in 12 to 18 months creates obsolescence problems even before the engineering model development (EMD) is complete. This is the type of problem now being faced by the prime contractors of U.S. aircraft currently under development. Discontinued commercial production of critical components will force programs into either a significant redesign or a costly lifetime buy.

Due to the mismatch in product life cycles, the use of COTS mandates the continual insertion of commercial technology. The challenge is to develop requirements, certification, and qualification processes that enable the continual replacement of elements during the entire life of the system without the expense of total system recertification and requalification. The entire system must be developed using a building block approach. The architecture must lend itself to the efficient, continual replacement of the building blocks as COTS products evolve. The enabling step in achieving the benefits of COTS is not in the selection of the right processor instruction set architecture (ISA) or interconnect protocol but instead is in the development of an architecture that cost-effectively supports the inevitable replacement of its elements during its service life. The ability to continually upgrade elements results in a system that continues to grow gracefully in capability and eliminates the need for very expensive and lengthy system upgrades.

For new platform aerospace mission systems to benefit from the inherent cost savings associated with COTS products, both the military establishment and the defense industry must focus early on integrated logistic support (ILS):

- Combine legacy and new product technology
- Schedule system additions/upgrades
- Schedule transition to new products
  - Parts obsolescence avoidance
  - Parts substitution
  - Cost optimal sparing.

Concentrating on the above objectives will also reduce the cost of future upgrades to existing platforms. However, neither this paper nor a symposium totally dedicated to the subject can be expected to answer all the questions associated with the above objectives. We can only offer some observations and illustrate hypothetical solutions we believe will improve system affordability.

4.0 OBSERVATIONS/HYPOTHETICAL SOLUTIONS

1. The financial welfare of our individual countries and people require us to develop lower cost aerospace mission systems. The U.S. Department of Defense (DoD) is moving aggressively to streamline the acquisition system. Passage of the Acquisition Streamlining Act in 1994 (FASTA 94) under than Deputy Secretary of Defense, Dr. William J. Perry, addressed use of commercial specifications and standards. The U.S. DoD is actively seeking to implement improvements in the acquisition process[1].
2. The defense industry must understand and, where savings are real, mimic commercial industries use of the open system commodity market.
3. COTS suppliers need to be monitored continually to assess changes in their business models that will impact military system procurement.
4. Open systems start with the use of both hardware and software interface standards. Creative building blocks that use interface standards and provide company profits keep the supplier engine running.
5. The defense industry and a typical commercial consumer place different environmental demands on products. This is perhaps the most complex task facing the defense industry – how to eliminate the need for expensive ROTS and MOTS components.
6. To achieve the potential benefits of COTS products, a new requirements, certification, and qualification methodology must be employed by the defense industry.

The methodology must support the inevitable insertion of new technology during the life cycle of the system.

7. The model for the COTS market is based on a much shorter product life cycle than the historical model for defense system platforms. Use of the COTS model will inevitably lead to the use of pre-planned product improvement (P^3I) by the defense industry.

The scope of this paper prevents us from providing an in-depth definition for P^3I. However, we will attempt to illustrate ongoing activities compatible with the above observations, hypothetical solutions, and the concept of P^3I.

5.0 ILLUSTRATIONS

The Lockheed Martin Tactical Defense System (TDS) division, located in Eagan, Minnesota, USA, has used the previous observations and hypothetical solutions to form a COTS-based P^3I strategy for next generation aerospace mission systems. Recognition of the need for a strategy began with participation on the U.S. Navy's Next Generation Computer Resources (NGCR) High Speed Data Transfer Network (HSDTN) working group. The objective of the NGCR HSDTN working group was to adopt a standard backplane interconnect network for military systems that would eliminate the bandwidth and scalability limitations of "party line" backplane buses.

In July, 1993, the HSDTN working group adopted the IEEE 1596-1992 Scalable Coherent Interface (SCI) as a standard backplane network. The SCI standard was originally created by international personnel from commercial industry and academia[2]. The standard was completed in 1992. The intent of the working group was to meet the growing need of next generation hardware and software for scalable interconnect bandwidth. The SCI protocol has since been adopted by the Society of Automotive Engineers (SAE) Aerospace International AS-2 Unified Network Interconnect Task (UNIT) working group for applications beyond the processor backplane including transactions between sensor and video subsystems. SCI utilizes point-to-point packet protocol compatible with traditional LAN message passing while providing low latency features required for cache-coherent, shared memory access. Bandwidth scalability is achieved by varying the interconnect topology, e.g., by using compatible ring, n-dimensional mesh, and/or switch interconnect schemes.

The increasing use and availability of commercial multiprocessing is being accompanied by a significant change in software architecture. Figure 4 illustrates what we perceive to be a major trend in future high performance multiprocessor systems. Current systems allocate application and operating system software to each node (unit processor or symmetrical multiprocessors). Two or more nodes form a distributed processing cluster (Figure 4, left). However, the performance of a distributed processing cluster decreases as operating system overhead for message exchange, interrupt processing, load balancing, fault recovery, etc., occurs.

The central processing unit or units (CPUs) within each node require on-chip cache and cache mechanisms to achieve their performance potential. "Support for synchronization and memory coherence are two important elements of [current CPU] chip design"[3]. The increased use of symmetrical multiprocessors combined with the availability of on-chip cache mechanisms provides the incentive for the software architecture change illustrated in the remainder of Figure 4.

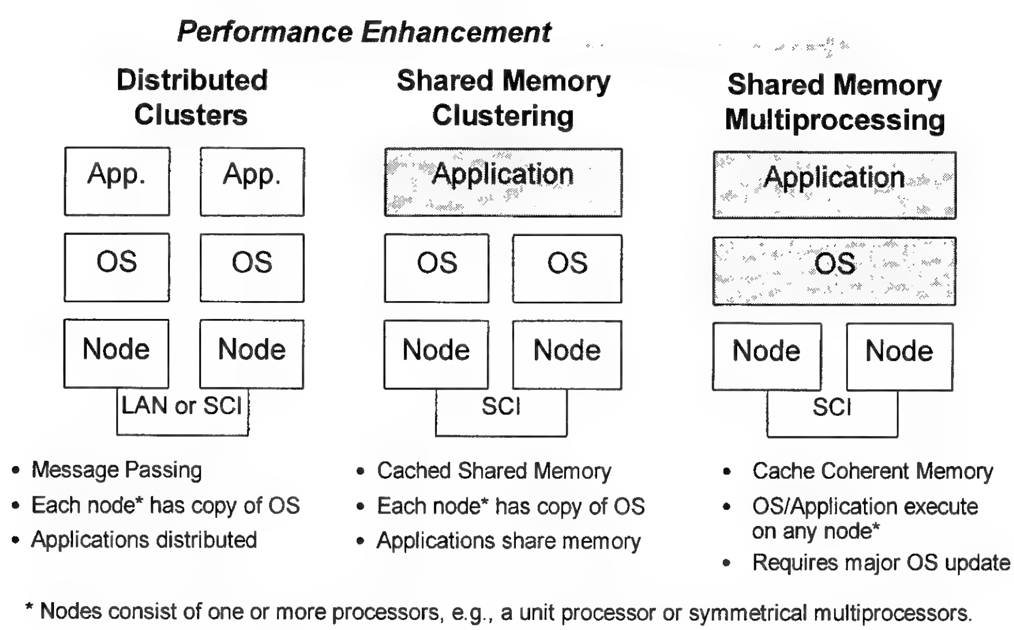

Figure 4. Commercial Trends Include Memory Sharing

Evidence is growing that the change will allow multiple CPUs to first, share a single copy of the application software (Figure 4, center) and ultimately, share a single copy of both the application and operating system software (Figure 4, right). This architecture reduces the need for memory, a significant advantage for aerospace mission systems.

Information (instructions or data) can be transferred directly from shared memory to the CPU cache. This eliminates the need to move information from one node's memory to the memory of another node and reduces operating system overhead. Movement of information directly from the memory in which it is located to the CPU cache reduces the number of memory references required. This change in software architecture is expected to increase system performance while reducing system cost.

Evidence of the software architecture change is illustrated by Intel's Commercial Multiprocessor System shown in Figure 5, the specification for which can be downloaded from the World Wide Web. The specification identifies the potential use of a single copy of the operating system for up to 256 processors[4].

Caching for multiprocessing has traditionally been limited by the scalability of backplane buses. This and similar needs for bandwidth is what led to the creation of SCI, IEEE 1596.

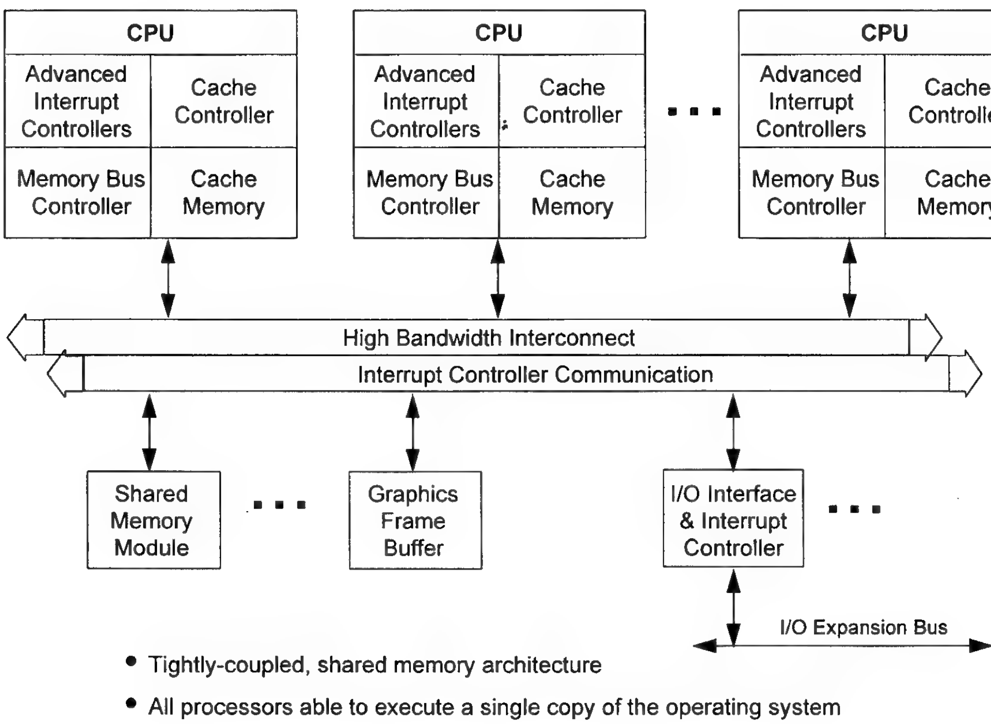

Figure 5. Commercial Multiprocessor Trend Illustration

The need for high performance aerospace mission systems resulted in the formulation of a task force comprised of U.S. Air Force, Navy, and Marine personnel. The task force selected SCI as a leading interconnect candidate for the next generation Joint Strike Fighter (JSF). The interconnect is illustrated in Figure 6 as the Unified Digital Avionics Network[5].

The SCI-based architecture permits processing modules to share memory or communicate by means of messages regardless of on which chassis they reside. This simplifies system upgrade and supports P^3I. For example, high performance processing modules for resource control and signal pre-processing can be located in the RF enclosure (as illustrated in Figure 6 for RF sensing) or in the Integrated Core Processor enclosure (as illustrated in Figure 6 for EO sensing). The evolving availability of commercial interface components enables the use of either a fiber optic or copper wire media and supports the flexible placement of modules. For example, it is now possible to install fiber optic cables for initial high performance RF or intermediate frequency (IF) communication between analog modules. Using P^3I, the analog modules can ultimately be replaced with digital modules as lower cost, higher performance analog-to-digital (A/D) converters become available. The fiber optic cables can now be used with SCI protocol for digital information transmission and control.

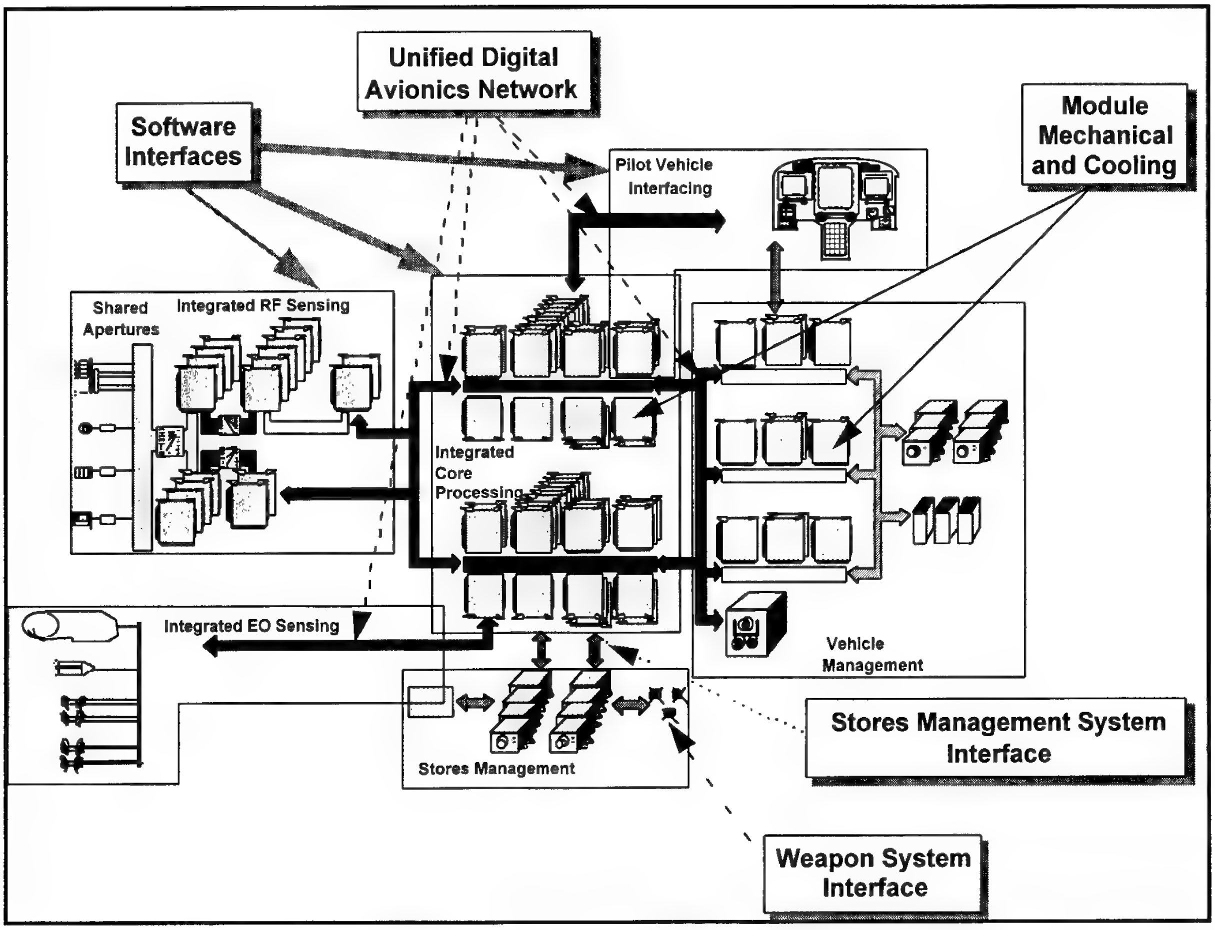

Figure 6. Advanced JSF Architecture Showing Interface Standardization

The availability of SCI command protocol for shared memory, message passing, or a combination of both enables the interface of legacy subsystems (e.g., the Vehicle Management System) with systems that are compatible with the trends outlined above. SCI simplifies system upgrade and provides the infrastructure for P^3I.

Cost/risk reduction for next generation aerospace mission systems will involve:

1. A mix of legacy systems and evolving COTS technology
2. Upgrades compatible with evolving threats
3. Component replacement based on the shorter life cycles of COTS products.

All require P^3I to benefit from commercial trends and the associated COTS products. Selection of the interconnect is, however, a key ingredient. The interface must be stable and sufficient, i.e., it must satisfy evolving information exchange paradigms and bandwidth requirements *beyond the life cycle of individual products*. For example, the interconnect of commercial systems historically started with the use of linear LANs. As system use increased, the requirement for additional bandwidth was satisfied using switches compatible with LAN protocol. We expect this commercial trend to be repeated for the SCI standard. For aerospace mission systems, switches will enable performance demanding upgrades for passive target identification, auto target recognition, etc.

The authors contend that for effective use of COTS in the military, defense contractors must become involved in the development of commercial products. At a minimum, this requires participation in open system standardization activities as described earlier. However, other alternatives are available. As a defense contractor, Lockheed Martin TDS opted to design an SCI switch capable of transparently replacing existing topologies. Available SCI topologies are shown in Figure 7. The ring and mesh topologies are currently available from commercial sources. The switch fabric, however, was designed by Lockheed Martin TDS to meet military system scalability, fault tolerance, and low latency requirements. Using low power CMOS technology, the switch will support an aggregate interconnect bandwidth of P(500 Mbytes/second) where P is the number of switch ports available. The switch is compatible with both military requirements and commercial SCI products and software trends. Combined with evolving commercial products, the switch has the potential to stabilize the interface of commercial products with their shorter product life cycles. As this paper is being written, Lockheed Martin TDS is finalizing plans to introduce the switch as a commercial product.

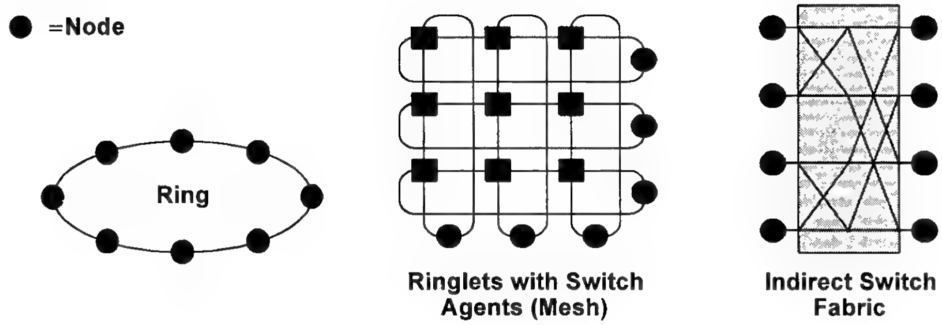

Figure 7. Topologies for SCI Bandwidth Scalability

The switch is illustrated in Figure 8 as part of a Scalable Multi-Processing System (SMPS). It is a multistage switch designed with layered redundant paths for fault tolerance and special features to reduce the blocking normally associated with multistage switches. The switch is shown attached to COTS SuperSPARC™ processing boards with SCI interfaces. Lockheed Martin TDS has also designed a Versa Module Eurocard (VME)/SCI gateway to serve as a bridge between VME/64 and SCI protocol. The VME/SCI gateway shown in Figure 8 allows the SMPS to use legacy building blocks, for example, VME graphics cards.

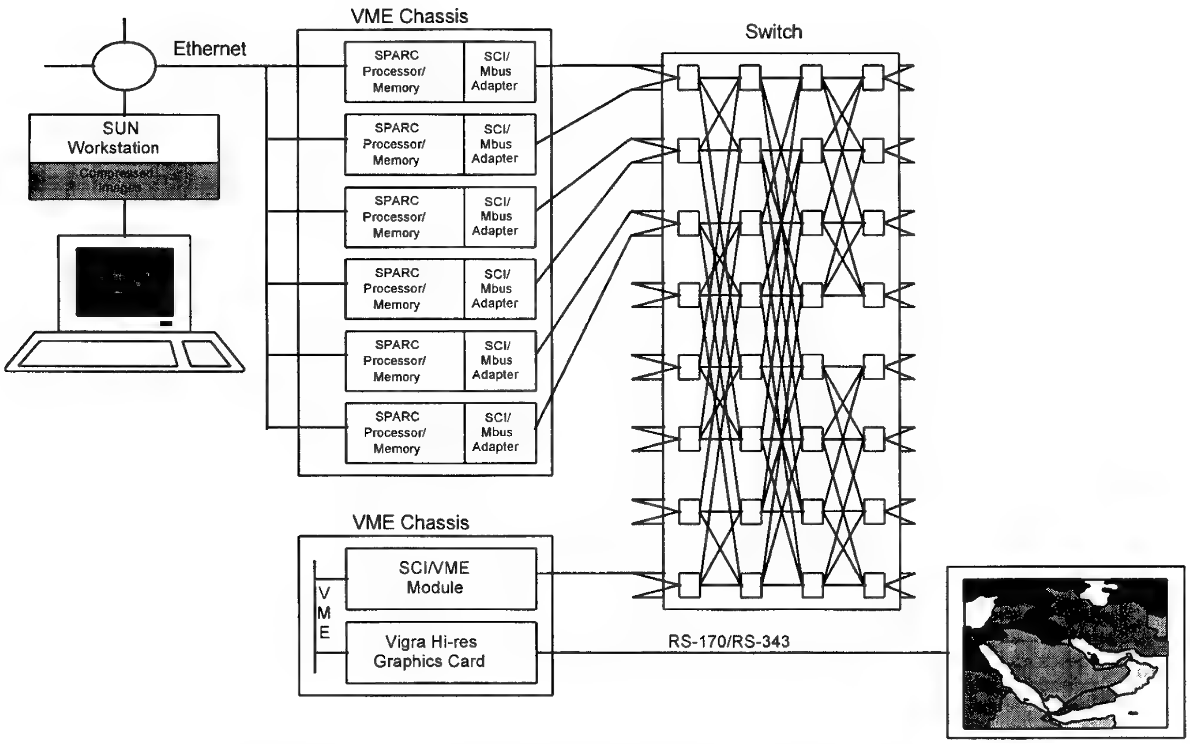

Figure 8. Prototype SCI-Based Scalable Multi-Processor System (SMPS)

To realize the full benefits of COTS products, the defense industry must also become involved in software standards for open systems. Lockheed Martin continues to be involved in the formulation of the Portable Operating System Interface for Computer Environment Standards (POSIX – IEEE 1003.1). More recently we have begun working with the U.S. DoD Open System Joint Task Force (OSJTF) to evaluate, and if deemed feasible, promote the efforts of a commercial working group for military real-time applications. The objective of the working group is to develop a Uniform Device Interface (UDI) enabling input/output (I/O) device drivers to be ported between COTS operating systems. A prototype, proof-of-concept UDI environment is currently under development (see Figure 9). Lockheed Martin will supply a metalanguage description for the SCI protocol, library functions, and a portable SCI driver for the UDI Environment.

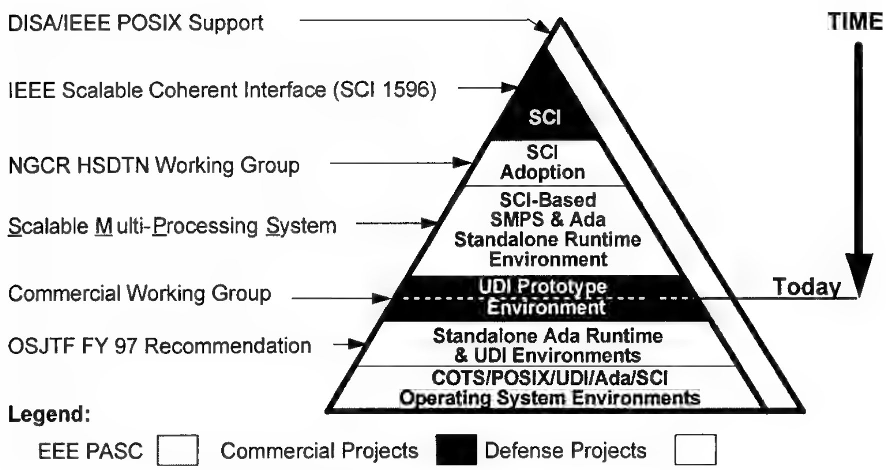

Figure 9. Open System Activities Supporting P^3I

Figure 9 also illustrates other activities in which the defense industry has been and needs to be involved. For example, POSIX standards are currently being defined by members of commercial and defense industry. However, the decision to utilize POSIX-compliant operating systems for aerospace mission systems will be determined by real-time requirements and the maturity of POSIX operating systems. To provide alternatives compatible with future COTS products, Lockheed Martin TDS has recommended that OSJTF integrate the UDI Environment with Ada stand-alone run-time environments as shown. Subsequently, Ada stand-alone run-time environments with POSIX compatible COTS portable drivers can be used with next generation aerospace mission systems.

6.0 CONCLUSIONS

The authors of this paper have concluded that COTS has "joined the military" and will become an increasingly larger part of aerospace mission systems for at least three reasons:

1. COTS provides greater capability at a lower cost
2. COTS supports continuous and graceful insertion of technology
3. COTS provides scalable system growth.

However, all of the above reasons directly contribute to the shortened life cycle of COTS products. The shortened life cycle will require the use of P^3I and the adoption of open system architectures for military systems. Standard hardware and software interfaces are the key to open systems.

Use of COTS-based open systems, together with P^3I, requires 1) the selection of an interconnect that satisfies commercial hardware/software trends, 2) the phased integration of legacy approaches with proven new approaches, and 3) the development of components that enable the integration of legacy components with newer technology. The defense industry must participate and invest in the development of all three.

Combining a COTS-based open system approach with P^3I was illustrated with activities currently underway at Lockheed Martin Tactical Defense Systems. Working with both defense and commercial technology leaders, Lockheed Martin adopted the use of the IEEE 1596 Scalable Coherent Interface for next generation aerospace mission systems. The protocol supports evolving software trends (multiprocessing shared memory), but will also support message-oriented legacy systems.

To improve the SCI interconnect for defense applications, a scalable, low-latency, fault-tolerant SCI switch was developed. Switch development was followed by the development of a VME/SCI bridge enabling legacy systems to work with COTS SCI products. Plans are underway to make the SCI switch available in the commercial market. This will provide military systems with the economy of scale, life cycle cost benefits and COTS product stability required for P^3I. Access to portable SCI software drivers is simultaneously being made available through the Uniform Driver Interface commercial working group and the U.S. DoD's Open System Joint Task Force.

This paper provides only an introduction to COTS capabilities/issues. Clearly, we could only scratch the surface. P^3I will require change to the acquisition processes including certification and qualification. This in turn will require the defense industry to better understand environmental requirements and the limitations of COTS components in the military.

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DEPARTMENT OF DEFENSE PERSPECTIVE ON OPEN SYSTEMS ARCHITECTURE

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1.0 SUMMARY. Due to downsizing of the U.S. defense budget, Department of Defense (DoD) does not have the resources to "go it alone" anymore. This situation warrants closer cooperation among the DoD services, the industrial base and our allies. There is much to be gained from the wealth of technology available from the commercial sector, especially in electronics for telecommunications, computing, display, sensing and signal processing. For these reasons, among others, recent DoD policies have placed emphasis on performance specifications and standards as opposed to using military specifications and standards. The DoD open systems initiative supports this new emphasis and the five "pillars" in transforming acquisition as delineated by the Honorable Paul Kaminski, Under Secretary of Defense for Acquisition and Technology:

(1) Right Size Our Infrastructure
(2) Reduce Cost of Weapon System Ownership
(3) Implement Acquisition Reform
(4) Leverage the National Industrial Base
(5) Leverage Our Allies' Industrial Base

The use of an open systems approach is motivated largely by the need (and the opportunity) to reduce the cost of ownership of weapons systems. Open systems are not the objective, rather an open systems approach is a means for program managers and their integrated product teams to achieve their fundamental program objectives of lower life cycle cost and improved performance. Open systems electronics applications include mechanical form factors, power supplies, radio/intermediate frequency (RF/IF) interfaces, and thermal management.

An open systems approach uses widely accepted, public consensus standards, that any vendor can use as the basis for system design. Having already proven itself in commercial telecommunications and computing, an open systems approach has been used successfully by the military Command, Control, Communications, Computers and Intelligence (C^4I) community and is now being implemented in the weapons systems acquisition community through the Open Systems Joint Task Force (OS-JTF). This paper will focus on the OS-JTF efforts to develop the foundations of open systems for weapon systems electronics.

2.0 BACKGROUND.

2.1 Open Systems Policy. On 29 November 1994, Dr. Kaminski signed a policy memorandum promulgating the open system approach for acquisition of weapons system electronics [1]. The policy applies to new developments as well as modifications to existing weapons systems and platforms. Although weapons systems must interface with C^4I systems, the policy does not apply directly to C^4I systems, communications networks, nor non-real-time data processing functions covered by other policy letters. The scope of system and subsystems elements for which the weapons systems electronics policy applies includes hardware, software, tools, architecture, and electrical, mechanical, and thermal interfaces.

Paper presented at the AGARD MSP Symposium on "Advanced Architectures for Aerospace Mission Systems", held in Istanbul, Turkey, 14-17 October 1996, and published in CP-581.

2.2 Formation of the Open Systems Joint Task Force (OS-JTF). Dr. Kaminski's open systems policy chartered the OS-JTF. The OS-JTF's vision is to "establish in DoD an open system approach as the foundation for all weapons systems acquisitions in order to lower life cycle costs and improve weapons system performance." The Task Force is chartered for approximately four years. The ultimate responsibility for execution of open systems acquisitions is vested in each Service's acquisition community.

The OS-JTF staff consists of a Director, a liaison from the Defense Information Systems Agency, a DoD program analyst, representatives from each of the three military services and support contractors. The Director reports directly to the Principal Deputy Under Secretary of Defense (Acquisition & Technology), the Honorable R. Noel Longuemare.

To achieve the open systems vision, the Task Force endeavors to:

- ❑ Assure that members of the DoD acquisition workforce, in particular program managers and lead engineers, understand the open systems policy and know how to implement it;
- ❑ Assure that electronics industry and standards bodies are aware of the policy and the new opportunities it presents;
- ❑ Identify opportunities for implementing open systems architectures;
- ❑ Share widely the lessons learned in open systems implementations;
- ❑ Establish key interface standards for use in weapons systems in the DoD; and
- ❑ Institutionalize the open systems approach across DoD so that the Task Force is no longer required.

Anticipated benefits of an open systems approach are:

- ❑ Reduced life cycle costs for weapons systems;
- ❑ Improved performance with greater intra-operability;
- ❑ Technology transparency for rapid upgrades;
- ❑ Improved interoperability for joint and allied warfighting;
- ❑ Closer cooperation between commercial and military electronics industries; and
- ❑ Improved international competitiveness of the U.S. electronics industry.

3.0 THE MOVE TO OPEN SYSTEMS.

3.1 Initially, most open systems discussions were narrowly focused in one dimension, i.e., along the lines of simply being "closed" versus "open" systems. Closed systems were regarded to be proprietary, secret, or patented, while open systems were based on standards which were agreed to and published by an accredited, consensus-based group. Over the past eighteen months, the Task Force has articulated a much broader view, allowing for a multi-dimensional model of open systems depicted in Figure 1. The first of several additional dimensions is "market acceptance". For a system to be truly open, it must have a broad market base as it does little good to have open system standards and specifications which are not supported by products. The desired operating regime for weapons systems acquisitions of the future is one with many suppliers, many customers, long life architectures and readily available technology upgrades.

3.2 Several other interrelated open systems dimensions are worthy of note: time; coverage or completeness; performance; and price. The outlook for open systems is not static--systems may migrate toward openness over time as a standard gains market acceptance or as the interface is made public in order to increase the market base. Specific open systems standards and interfaces may have varying degrees of applicability to weapons systems. Weapons systems must generally perform in real-time and in a deterministic manner. Extensions or adaptations to open standards, while not generally desired, may be required to meet the

unique needs of a particular weapons system. For example, the design of tactical aircraft places a premium on weight, volume and environmental requirements, and therefore may require a different set of trade-offs in performance with respect to open system standards.

4.0 THE OPEN SYSTEMS APPROACH.

An open systems approach is a business approach for developing affordable weapons systems. This approach chooses from among open system, de facto, and Government specifications and standards, and commercial practices, products and interface standards to provide quick access to technologies that maximize combat effectiveness under a given cost constraint [2]. The iterative nature of the open systems approach is depicted in Figure 2 and is discussed in the following paragraphs.

4.1 The Architectures. The open systems approach advocated by the OS-JTF is based, in part, on a concept of describing the electronic portion of weapons systems using a standards based architecture. This architecture consists of a technical reference model and the standards that describe the interfaces and services between the components. This has been defined as a "technical architecture" and may be compared to a set of building codes. These building codes help industry establish and maintain an orderly and competitive marketplace. The "technical architecture" is distinguished from the "operational architecture" which is defined by the weapons system user and a "system architecture" which is the particular system designed to meet a particular performance requirement with specific hardware and software based on the technical architecture.

4.2 Open Systems Engineering Process. The traditional systems engineering process must be modified as depicted in Figure 2 to accommodate the changes brought about by the open systems process. The DoD and industry must work together within an open systems framework to select and apply the appropriate weapons systems standards. This process must consider the entire weapons system life cycle.

4.2.1 Development and Selection of Standards. Just as with building codes, industry has the primary role of defining, developing and maintaining the standards that will form the basis for weapons system electronics. These standards must address both hardware and software and include the non-digital areas such as packaging (physical interface), power, cooling and analog signals.

Although industry has a dominant role, the DoD has an essential part to play as well. DoD customers must help industry define the unique weapons system requirements. To the extent possible, it is helpful for the DoD customers to speak with one voice and appropriately narrow some design standards to allow industry to respond efficiently to our needs. A model for this customer consortium is the recent work of the automobile industry to jointly define key standards for the products provided by their common supplier base. In this sense, the DoD must select or recognize the interface standards to be used for our products.

Selection of standards agreed to by accredited, consensus-based standards bodies (i.e. open standards), and in widespread use, is highly desirable. They frequently have a broad base of supplier and customer acceptance, are mature technically and are chosen fairly. Some proprietary standards have become *de facto* standards through widespread market acceptance. Because of our desire to build weapons systems based on commercial electronics technology and the industrial base, both consensus based and *de facto* standards are critical to us. For that reason, the OS-JTF has chartered the Committee on Open Electronics Standards (COES) to harmonize the many on-going architecture efforts and extend the Joint Technical Architecture [3] to include weapon systems. COES will not develop its own standards but will identify weapon system domain stakeholders who will *designate* open

standards and develop domain technical architectures. These standards will be selected based on an assessment of both government and industry standardization efforts to focus on specific weapons systems community needs. The current domains under consideration by COES are depicted in Figure 3.

4.2.2 Application of Standards. The standards applied to create a system architecture must be based on performance requirements and the business case for the acquisition strategy. Many factors must be weighed in the decisions of what standards should be applied. These factors include: the support strategy (maintenance and repair and spares procurement approaches), the strategy for evolution and upgrade of the product with regard for life of the technology, risk management, market research and life-cycle cost.

The application of standards may vary for different portions of the system. The government maintains configuration control above this level of application. Below this level, industry must be given maximum latitude to make design decisions without interference. The contractor must retain rights to his designs and requirements for design disclosure should be minimized. This will allow contractors to exploit innovation, process improvement and new technology for their benefit as well as that of DoD. Each program should choose how to apply these architectural standards or building codes for maximum benefit. The product descriptions that make up the system architecture and which include the interface, interoperability and performance requirements are also called Form, Fit, Function and Interface (F^3I). F^3I acquisition is a strategy for dealing with obsolescence, diminishing manufacturing sources, acquisition workforce reductions, and implementing acquisition reform.

Domain product lines contain a group of building blocks (products, services, tools and processes) to constrain or enhance systems engineering process to meet specialized domain needs.

The level of interfaces to be defined is dependent upon the specific product or system to be acquired and supported. Examples include an entire avionics suite, a major avionics subsystem, and a module within an avionics function. These key interface definitions provide the framework for an open system approach. The architecture should define an "atomic" level. Interfaces at this level and above should conform to the defined standards. Design below the "atomic" level will be under the control of the suppliers. The "atomic" level should coincide with the repairable level. There should be no organic repair below the "atomic" level. The choice of the "atomic" level and the associated standards should be based on the anticipated life cycle cost, performance, risk and business considerations.

5.0 IMPLEMENTATION.

5.1 Open Systems Training. The Task Force has coordinated the development of several open systems educational products to increase the DoD acquisition workforce's knowledge of issues and practices. First, a basic course has been developed by the Software Engineering Institute (SEI) of Carnegie Mellon University, entitled "Open Systems: Promises and Pitfalls". This 2-1/2 day basic course is given periodically throughout the year. Second, the Task Force has sponsored the development of a four-hour executive presentation for senior acquisition officials, program managers and their functional staff. These efforts will eventually be transferred to the Defense Acquisition University and the Services for on-going training of the acquisition workforce.

5.2 Standards Activities. The OS-JTF, in conjunction with numerous standards bodies, government and contractor efforts, is sponsoring investigations of a number of standards activities. These include the definition of Ada language bindings (X/Open Transport Interface and Sockets), Real-Time

Extension of Portable Operating System for Unix (POSIX), interconnect technology trade studies (Scaleable Coherent Interface/Real-Time, Asynchronous Transfer Mode and Fibre Channel), radio frequency standards (Integrated Sensor System) and a technical reference model (Generic Open Architecture).

5.3 Demonstration Programs. The Air Force Open System Implementation Plan [4] fostered the notion that a series of demonstration programs would be effective in accelerating the acceptance of open systems approaches. On 15 February 1996, Mr Longuemare designated two avionics modernization efforts as open systems demonstration programs: the U.S. Marine Corps AV-8B Open System Core Avionics Requirements (OSCAR) and the U.S. Air Force F-15 Multi-Purpose Display Processor, shown in Figures 4 and 5. These efforts were identified by their respective Program Executive Officers as having significant open systems potential.

The demonstrations are currently being planned and executed through a Joint Steering Committee consisting of members from the cognizant program offices, the OS-JTF and McDonnell Douglas Aerospace and its suppliers. A major objective of the demonstration programs is to quantify the benefits of the open systems approach in meeting specific weapons systems requirements. The demonstration programs will not only focus on technical issues, but will seek to resolve the many business issues facing the DoD and industry as we move to open system acquisitions.

Closely related to the above demonstrations is an Open Systems Ada Technology (OSAT) demonstration jointly funded by the Ada Joint Program Office, the Joint Strike Fighter Program Office and the OS-JTF. This effort will prove the feasibility of using Ada95 in a real-time application, a Runge-Kutta algorithm hosted in a PowerPC processor installed in an AV-8B. The flight demonstration is scheduled for December 1996.

6.0 CONCLUSION. Creation of a technical architecture and its broad application to open systems will allow industry to develop competing products that meet our needs. They will be able to innovate and apply new technology and processes to improve performance and reduce costs within this planning structure. Program managers will be able to take advantage of electronics technology developed for the private sector, increased competition and product upgrades based on F^3I product descriptions and long-lived architectures rather than sole source suppliers. We will also be better able to avoid obsolescence issues by being better positioned to apply new technology to replace obsolete and no longer available or supportable technology. The open system approach provides new opportunities for life cycle support of DoD weapon systems. The move toward open systems has begun in earnest with the release of a DoD policy, development of training courses for the acquisition workforce, establishment of some demonstration programs, and publication of Component/Service Deployment Plans. Updated information regarding the progress toward open systems in DoD is published periodically on the Task Force's World Wide Web Home Page [5]. How far DoD moves along the path to true openness for affordable weapons systems in the future depends, in part, on the success of the demonstration programs, communication of lessons learned and the willingness of the workforce to embrace these emerging concepts.

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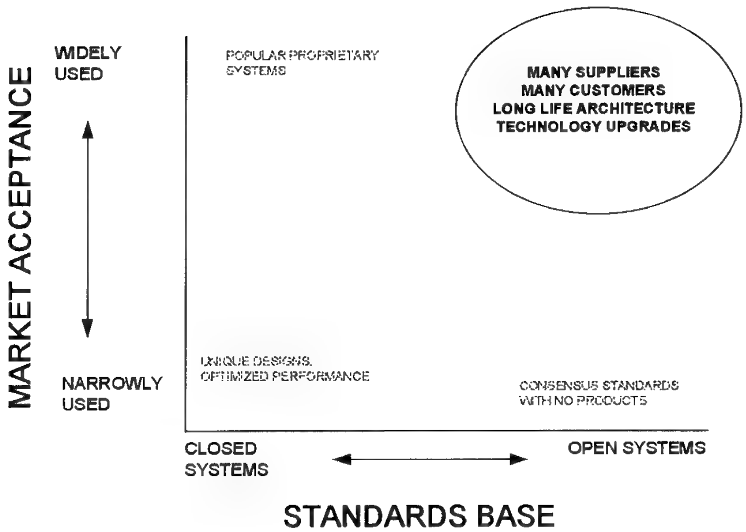

FIGURE 1. Move to Open Systems

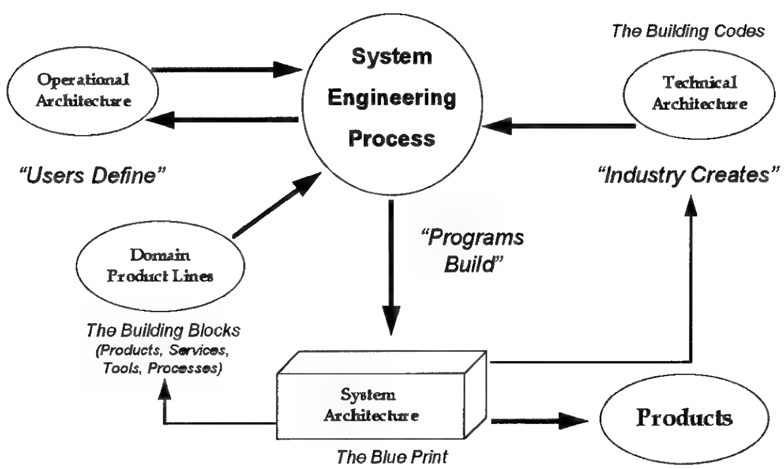

FIGURE 2. The Open Systems Approach

DOMAINS	TYPE
Aviation Space Vehicles Maritime Vessels Automated Test Equipment Ground Vehicles Missile Defense Systems Missiles Munitions Soldier Systems Surveillance/Reconnaissance	Weapon Systems
Surveillance/Reconnaissance Command & Control Communications Intelligence Information Warfare	C4I Systems

DOMAINS	TYPE
Human Resources Mgmt.	
Medical Sustaining Finance & Accounting Base Logistics & Material Acquisition Legal Mapping	Information Systems
Training Devices Simulators (testbeds) Wargaming/Modeling & Simulation	Training/ Simulation Systems

FIGURE 3. Proposed DoD Domains (COES)

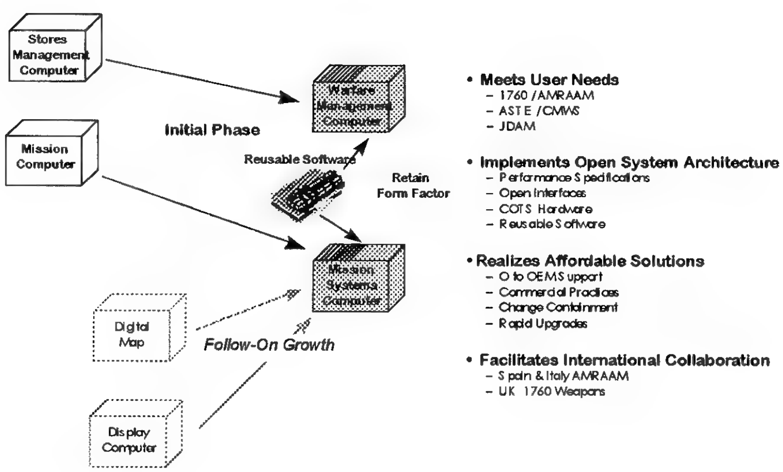

FIGURE 4. AV-8B Open System Core Avionics Requirements

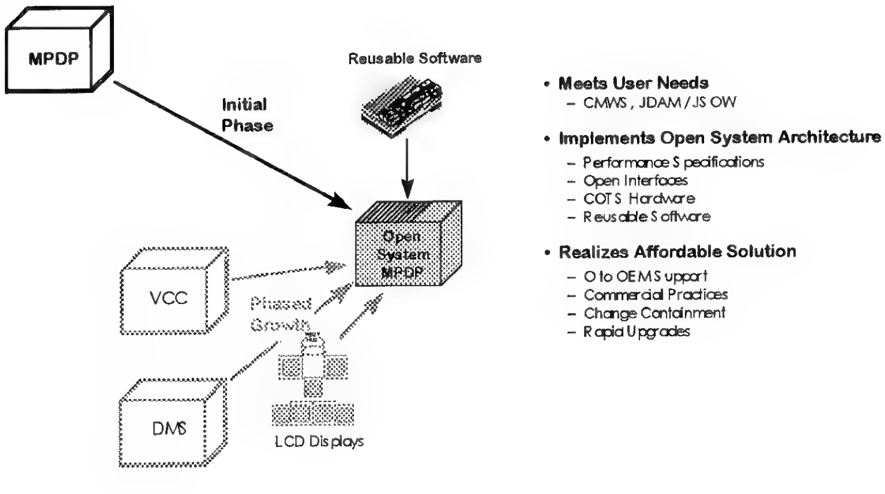

FIGURE 5. USAF F-15 Multi-Purpose Display Processor (MPDP)

MODULAR AVIONICS SYSTEM ARCHITECTURE DEFINITION IN THE EUCLID RESEARCH AND TECHNOLOGY PROGRAMME 4.1: METHODOLOGY AND RESULTS

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SUMMARY

The European Cooperation for Long Term in Defense (EUCLID) Research and Technology Programme (RTP) 4.1 "Modular Avionic Harmonization Study" (Ref. 1) is a joint programme carried out by France, Germany, Italy, Netherlands, Spain and United Kingdom, aiming to harmonize modular avionic concepts among the aforementioned nations, thus preparing a common European basis for the future development of modular avionics platforms, taking as reference the 2005/2010 in service date time frame.
The work has been developed through five work packages, dedicated respectively to General Requirements for Modular Avionics, System Architecture Definition and Risk Assessment, Technology Programmes, Modular Avionics Support Facilities, Identification of a Roadmap for Modular Avionics.
This paper presents an overview of the methodology that has been adopted to come to the definition of a modular avionic system architecture which is capable to satisfy a defined set of functional requirements, in presence of technical constraints of various nature resulting from technology assessments carried out during the programme. The paper discusses the following subjects:

* The different functional areas to be covered by an avionic system tailored on an envelope of operational requirements.
* The different categories of functional/physical elements which compose the modular system.
* Those requirements, among the set of driving functional requirements taken as reference in the course of the study, whose impact has been so relevant to drive or condition the architectural study.
* Technical requirements and constraints associated to the physical elements, having a direct impact on the system architecture model.
* The basic characteristics and an outline of the proposed architectural model, how it has proceeded from the above functional/technical requirements, and how it incorporates important features, such as an adequate capability to tolerate faults by reconfiguration and to perform data fusion at various levels.
* Limits of the architectural study carried out.

1. INTRODUCTION

Integrated modular avionics architectures are expected to feature substantial advantages, with respect to current avionics, from both the life cycle cost and the performances viewpoint. While it is almost taken for granted that modular architectures will equip next generation aircrafts, the attention is focused also on the possibility of modular upgrades. Modernization of existing aircrafts with a complete modular suite should be considered feasible once constraints, such as available physical space and interfaces with the electrical generation system, are met. On the other hand, the possibility of retaining part of the existing avionic system should be evaluated more carefully, as for feasibility and effectiveness of the proposed solutions.
In order to implement modular avionics in a project, whether centered on a new target platform or on upgrades of current ones, research activities have to be carried out in different directions, and, having to cope with the availability of limited resources, with different priorities.
In the USA the concept has been developed by programmes such as PAVE PILLAR, and, more recently, PAVE PACE. The concepts defined in PAVE PILLAR have been already transitioned to the F-22 Advanced Tactical Fighter and RAH-66 Helicopter (Ref. 2). European Nations have approached the subject with national research programmes and joint research programmes, such as the Allied Standards Avionic Architecture Council (ASAAC) phase 1 and 2, and the programmes incorporated in the Common European Priority Area (CEPA) 4 within the EUCLID frame. It should be underlined that ASAAC is not strictly speaking a European programme, as phase 1 has seen the participation of France Germany, United Kingdom and the USA.
As stated in the summary, this paper is focused on the portion of work that, within RTP4.1, has been developed about the topic of system architecture definition. For completeness, it is nevertheless necessary to briefly report the overall structure of the programme.

2. OVERALL STRUCTURE OF THE PROGRAMME

RTP4.1 has been the first programme carried out in the CEPA 4 "Modular Avionics", leaded by Germany within the EUCLID frame, with participating nations France, Germany, Italy, Netherlands, Spain, United Kingdom. It began in February '94, and is technically concluded while this paper is being written.

Paper presented at the AGARD MSP Symposium on "Advanced Architectures for Aerospace Mission Systems", held in Istanbul, Turkey, 14-17 October 1996, and published in CP-581.

The work has been developed through the following work packages (WP):

WP1: General Requirements for Modular Avionics, mainly devoted to the definition of general mission requirements and operational aspects for different airborne platforms.

WP2: System Architecture Definition and Risk Assessment, aimed to the definition of a suitable system architecture proposal for integrated modular avionics. This paper is focused on this work package.

WP3: Technology Programmes, devoted to the study of technology areas deemed essential for modular avionics system development. The examined technology domains have been primarily those affecting the processing digital core of the system (Networks, Packaging, Data/Signal Processing, Software), while external areas (Radio Frequency (RF), Electro Optical (EO) sensors) have been considered at the level necessary for core definition.

WP4: Modular Avionic Support Facilities, dedicated to the study of Integrated Project Support Environment and HW/SW/System Development tools/facilities.

WP5: Identification of a Roadmap for Modular Avionics, planning a way ahead for further development of modular avionics based on European technologies.

3. BOUNDARIES OF THE ARCHITECTURAL STUDY AND ACTIVITY FLOW

The following consideration will help in looking at the results of the study with the correct perspective.

- In defining the main building blocks and Europe based technologies for application in a modular avionic architecture, the study has taken as reference the in-service time frame 2005- 2010. Roadmap studies have finally suggested as feasible an in-service date of about 2015 for a new fast jet, while a nearer time frame (2010) can be assumed for retrofit programmes.

- No attempt has been made in trying to define the complete requirements for a specific aircraft or helicopter. This because of the necessity not to specialize the study, from the beginning, to a specific platform or to an exhaustive, but to some extent arbitrary, set of operational requirements. This approach seems correct if compared with important features of the modular approach: improved adaptability and an open architecture. Mission profiles which, in association with platform types, have been considered, and whose general requirements have been described, are:

  1. Air to Air
  2. Air to Ground
  3. Maritime
  4. Intelligence Gathering
  5. Surveillance
  6. Transport

- The study has been focused on the digital core of the system (see para. 4 for definition) while the remainder of the system has been mainly considered with regard to its interfaces with the core. As PAVE PACE studies indicate, great advantages are promised by the extension of the modular/integration concepts toward the surviving analog portion of the sensors set (readers not acquainted with the new sensor concept implicit in integrated modular avionics will find more detail in para 5.1 of this paper). While a through analysis in this direction was outside the scope of the study, the subject has been taken in account with a twofold strategy:

1. Carry out a preliminary examination of Radar, Communication / Navigation / Identification (CNI) and EO sensor front-ends, highlighting commonalities and possible analog module sets. The result can constitute the starting point for possible dedicated future activities

2. Indicate architectural alternatives and technology solutions for the analog sensor / digital core interface which are open to the evolution toward the sensor integration area.

- Safety critical functions have been considered external to the avionic system core (see para. 5.5). A Vehicle / Stores Control Block has been interfaced to the core, but not furtherly analyzed.

The pictorial description of Fig. 1 will help in clarifying the methodology applied for the architectural study, creating a correspondence between the flow of activities and the topics discussed in the following paragraphs.

4. RATIONALE FOR INTEGRATED MODULAR AVIONICS: COMMONALITIES AND FUNCTIONAL PARTITIONING

In order to carry out an integration of a set of functions, commonalities must be identified among them. Common elements will then be realized with modular building blocks (hardware and software), and will be combined with non-common elements and connection facilities in a system architecture. The approach, if properly applied, will bring those advantages in terms of Life Cycle Costs and performances which have been pointed out many times in literature, and justify the effort of the avionic community in pursuing integrated modular architectures. According to this philosophy, we should try to describe the system without be bounded to traditional physical blocks or subsystems. We therefore start noticing how the most general avionic system is a collection of Generators, Processors and Utilizers, connected by means of Channels. Information is originated, processed and supplied, flowing through logical successive stages, exploiting services supplied by *system elements*. Each avionic function will relay at least on a subset of these elements. A generic chain of system elements is shown in Fig.2 particularized, as for the analog stages, to an RF application:

- Sensor / Emitter Heads: mechanical / electrical sensing or emitting surfaces / components.

- Signal Conditioning: stage receiving and converting the sensed signal, or supplying signals in forms usable by emitters. As for RF applications, this stage will be splitted in RF and Intermediate Frequency (IF) sub-stages.
- Pre-Processing: essentially demodulation, analog to digital (A/D) conversion, parallel/serial conversion.

These stages tend, due to their analog nature, to be bounded to the physical properties of the specific emission, that is, tend to be application specific. Prosecuting our analysis, we step into the digital world. Digitized streams of data tend, due to their nature, to be processed more homogeneously then the analog signals which originate them. The following system elements can be individuated:

- Signal Processing: dedicated to extract information from raw, high rate digital data, by means of operations such as filtering, smoothing, correlation, vector/matrix operations, averaging, thresolding, Fourier transforms, etc...
- Data Processing: general purpose processing, acting on relatively low data rate, but performing high level complex operations (e.g. moding, threat classification, database management, etc...).
- Control Processing: control of system status and crew interface. Herein, we will define it comprehensive of the processing required for graphic generation. This stage will therefore carry out complex logical operations on a huge amount of status and control data, and also image manipulation tasks.

Signal, Data and Control processing are indeed system elements for which a great amount of commonal presence across the various functions can be envisaged.
This results more clearly briefly listing the main functions carried out by the avionic system associated to a generic weapon platform and grouping them in macro-areas, as shown in Tab. 1. The result is that, together with sensors and actuators front-ends, and communication links, a cooperation of the aforementioned digital system elements is sufficient to carry out any of the indicated subfunctions.

Concluding the analysis of the chain of system elements, we finally find the analog front-ends of Displays & Controls and Effectors (synthesized in the figure as "Crew"), any computation stage at this level being already considered before as Control Processing.

The avionics system "core" is, from a functional point of view, the collection of Signal, Data, Control Processing system elements, connected, by means of proper digital communication channels, among them and toward sensors and actuators front-ends, and other external systems if necessary. This concept is expressed in Fig. 2, which highlights the processing elements to be integrated in the core, creating a so called Integrated Digital Processing Block (IDPB).
The system elements individuated as components of the digital core are to be regarded as functionalities, to be provided by physical modular units.

5. DRIVING REQUIREMENTS FOR THE ARCHITECTURAL STUDY

The starting point for the definition of an architectural proposal is the availability of a set of functional requirements and design criteria stated clearly, in a form which can steer the architecture topology definition ideally without intermediate translation steps. In their turn, functional requirements and general design criteria are to be derived from an analysis of more general requirements (Operational and Mission requirements) together with Life Cycle Costs considerations.
In RTP4.1, general requirements have been defined for a wide set of missions / platforms. In order to extract from these a consistent and realistic set of functional requirements, an analysis has been carried out, aimed to identify the mission profile, among those described, that deserves to be considered as driver of the study. The Air to Ground mission profile has been selected as driver, on the base of the following considerations: it features more demanding sensors and crew interface requirements than the Air to Air one, similar to Maritime but with higher requirements as for effectiveness of crew interface. Transport and Surveillance missions do not issue top requirements. Intelligence Gathering, while very demanding as for sensors and crew interface, is too specific to be qualified as driver for the study.

Making reference to Fig. 1, considering:

1. The set of general requirements associated to the Air to Ground mission profile.
2. Life Cycle Cost general criteria (synthetically listed in Fig 1).
3. Commonalities and functional partitioning.
4. Cross checks with those results of technology studies oriented to interface requirements definition

it has been possible to come to the definition of a set of *functional requirements* and *design criteria* to be taken as drivers for the architectural study. These are listed in the following, *limitedly to those aspects which have directly conditioned the architectural study.*

5.1 Sensor Control Processing and Interface Requirements

As already pointed out, the maximization of the integration of digital processing resources in the system core is bounded with a definite simplification of sensors with respect to current implementations. Data and signal processing stages which are today incorporated in the sensor's LRUs must be extracted and taken at core level. This concept is expressed in Fig. 2 for a generic radio frequency (RF) application. One result is, indeed, having to deal, in output from the sensors, with digitized raw signals characterized by much higher bandwidth and stronger real time / latency requirements than before.

Considering the set of sensors which have to be available to carry out the Air to Ground mission taken as reference, we find that, from the requirements point of view, they can be almost entirely grouped in four macro-areas, specifically Multimode Radar, EO, Integrated Defensive Aids and CNI. Table 2 reports quantitative processing and interface requirements for these sensor areas. In reading the table, the following should be considered:

- The unit GFLOPS indicates a number of billion of floating point operations per second, and is considered, relatively to the general approach that is possible to apply at this stage, representative for signal processing performances.
- The unit MIPS indicates the number of million of instructions per second, pertaining to an averagely representative instruction set. It is used to quote data processing requirements.
- The output data rate refers to the flow of digitized raw data to be transferred from the sensor area to the core processing, and is expressed in billion of bit per second (Gbit/s).
- The iteration time refers to the sampling rate of the digitized data to be processed in the core.
- The figures in the table are projections, 10-15 years ahead, of values valid for present sensors, and should be considered as estimates.

5.2 Mission / System Control Processing Requirements

This functional layer will gather, in addition to improved traditional avionic functions carrying out navigation, weapon aiming, system moding, initialization, diagnostics tasks, new features definitely characterizing the next generation of military avionics, dealing with data fusion. Mission requirements call in fact for an high level of integration as for information presented to the crew, especially for a platform like the one selected as driver of the study.
It is possible to distinguish between two level of data fusion:

Fusion of processed information: data outcoming from signal / data processing stages, carrying meaningful information about different mission aspects, can be furtherly processed in order to extract from them a new set of "fused", improved information. Such a process can be applied, for example, to generate a best flight path, starting from navigation data, fuel consumption data, mission data base, threat localization / classification data, obstacles recognition data, etc...It is possible to think about an extended use of advanced processing techniques, but the pilot will have to preserve the possibility to effectively control the system.
Resources required to run this kind of high level data fusion are based on data processing system elements.

Fusion of raw data: digitized raw data entering the system core from the sensors' front end interfaces can be fused by means of signal / image processing algorithms, in order to exploit the characteristics of the different sensors, and enhance the overall quality of the result. Image fusion is a very promising application of this concept. For example, fluxes of signals carrying unprocessed images derived from EO and Radar sensors can be combined advantageously, providing performance enhancements. Additional candidates sources are stored digitized maps. It has also been demonstrated that fusion algorithms can be run with benefit over images produced by two (or more) different IR sensors.
Resources required to run this kind of low level data fusion are both signal and data processing system elements.

Overall requirements for the mission / system control processing function are estimated as follows:

Data Processing: 2000 MIPS
Signal Processing: 2-4 GFLOPS (rough estimate)
Memory: 4 Gbyte (mostly needed for map generation).

5.3 Crew Interface Control Requirements

The need has been envisaged to interface a set of elements, among which the most demanding and dimensioning from the point of view of a preliminary architecture definition are 1 Head-Up Display, 1 Helmet Mounted Display and 6 Head Down Liquid Crystal Multifunction Displays. This statement results directly from the adoption of the Air to Ground mission as the driving one, with pilot and co-pilot. New displays will be inherently digital by nature, and there are significative advantages to be gained in realizing them as "dumb" displays, with no incorporated graphic processing capability. These advantages range from size and power dissipation of the display themselves, to the centralized generation of video signals in the digital core, having beneficial effects on control and flexibility of the system. Digital raw pixel-level video signals will therefore be distributed from the system core to the display system, with bandwidths of the single channel ranging from 600 Mbit/s up to 1.7 Gbit/s. Proper image manipulation resources will have to be integrated in the digital core.

5.4 Networking Requirements

Networking is certainly a crucial topic for future integrated avionics. Even looking solely at the necessary available bandwidth, it is certainly true that it grows proportionally with the available processing power, and this grows of orders of magnitude with each new processor generation. Moreover, the nature of integrated avionics contributes to magnify the criticality of networking with respect to the federated approach. Two main different kinds of data transmissions are present in the system:

- *Long duration high data rate*, essentially streaming data of very high data rates from / to sensors and videos
- *Short duration lower bandwidth*, discrete packetized transmissions of control and status data

but there is a fundamental difference in the way current avionic systems and integrated avionics deal with these kinds of traffic.

Federated avionics (modern in-service avionics) is concerned essentially with low data rate digital traffic, being the system-wide circulation of high data rate traffic avoided by locally performed computing (e.g.: in sensors' line replaceable units) or by transmission of analog signals on dedicated connections.

Integrated avionics must on the contrary deal with digitized data traffic of both kinds above mentioned. It is in fact sufficient to consider that the request for high integration among homogeneous functions, and wide data fusion, calls for networks that connect the multitude of aircrafts sensors directly with signal and data processing elements integrated in the digital core, routing digital traffic, typically characterized by high band and long duration, with very stringent real time requirements, due to the very limited latencies necessary to sustain tight close loop sensors controls. Of course, bursty data traffic is present too, and will have to be circulated as well in the system. It can be underlined how it is usually more effective to approach with two different communication philosophies the transmission of the two kinds of traffic. It is well known, from modern communication criteria, that circuit-switching techniques are in general well suited for long duration transmissions, while packet-switching techniques are well adaptable to bursty traffic.

After these preliminary considerations, let us list more systematically the most important requirements applicable to the interconnection subsystem for integrated modular avionics.

- Use of a *common interconnect network*, addressing both backplane and system level, and with no logical difference between cabinet internal and cabinet external connections. This will allow effective control of latencies, as no bridging device will be required, and will increase standardization.
- Routing of both long duration (streaming) and short duration (bursty) data transfers.
- Capability to be configured within specified limits of growth.
- Support of fault tolerant operation
- Support connection of up to 256 physical entities.
- Assure very limited maximum transfer latencies, specified to be more stringent for control than for data traffic.
- Assure very limited maximum linking / unlinking times.
- Support data transfer rates of at least 2 Gbit/s. This requirement descends directly from previous considerations about raw digitized data produced by sensors realized according to the new sensor concept, and from the necessity to route high band digitized images to the crew interfaces.
- Support control / status information transfer rate of 200 Mbit/s.
- Fiber optic is required as physical transmission media.

Many other requirements have been stated concerning the communication subsystem, the specification of which is not relevant for the scope of this paper.

5.5 Fault Tolerance Requirement

One of the major promises of modular architectures is a significative improvement of the overall system fault tolerance, realized by means of extended dynamic reconfiguration capabilities. Among the specified operational requirements, the following have been found applicable to this system aspect:

- Safety Critical Functions shall contribute to the mean rate of major accident with a probability not exceeding 10exp(-6) per flight hour.
- Survival Critical Functions, necessary for the aircraft to survive in a high threat environment, shall fail with a probability not exceeding 10exp(-5) per flight hour
- The mission shall be successfully completed with a probability not less than 0.95.
- The system must be designed to degrade gracefully

Moreover, a general design target of sufficient system availability after 150 hours without maintenance has been indicated as desirable.
In general, it must be observed that avionics is only a part of the total weapon system, and the responsibility of occurrence of any kind of fault is to be apportioned among systems hosted by the aircraft, finally individuating the "responsibility" of avionics. Not only, but, being here interested in the digital core of the integrated system, we should distinguish it from the rest of the avionic system, and we will find from available literature data that the core is responsible for about 20% of the total avionic system failures. In view of the above, it can be observed that modular avionics offers a chance to improve the reliability of a system, but there is not much sense in concentrating efforts on the core without improving in parallel the analog sensor area.
A rigorous approach to core reliability would require to provide for each function a configuration of elements assuring both:

a. The reliability level required, distinctly, for flight, survival, mission critical functions.

b. The availability level required (150 hours without maintenance resulting in a proper availability probability.

In order to apply the above procedure, reliability figures are needed for all the physical components of the system core. Even if these physical elements will be identified later in this paper, it is worth to observe already now that, defining the modular core elements as per para. 6 of this paper, we should make hypothesis not only on the digital processing modules reliability figures, but also on power supply and network

components. In particular in the case of network components, failure modes and reliability figures are not easy to be figured out, presently, without stepping into arbitrariness.
It has therefore been decided to discard the rigorous approach (which should be considered, nevertheless, an interesting exercise to be made, in the expectation of specific reliability figures), and adopt a second approach, based on the general operational requirement calling for graceful degradation. This has been interpreted with a requirement, based on evaluations about the evolution of the present systems capability to tolerate faults, synthesized here as follows:

Event	n° of faults	Functional Status
1	2	full functionality
2	2+1	minor degradation
3	2+1+1	heavy degradation
4	2+1+1+1	function loss

Event 1: failure of 2 components, which may be of the same type.
Event 2: failure of 3 components, of 2 or 3 different types
Event 3: failure of 4 components, of 2 or more different types.
...
"Component" is to be intended as element of the system core.

It has been considered that this requirement (to be regarded as minimum, further improvements being desirable) would have promoted a useful effort in organizing the system in such a way to provide a good reliability level, by means of the identification of reconfiguration paths and criteria.

It must be pointed out that this requirement is not considered applicable for flight critical functions. These have been in fact encapsulated, allowing interfaces with the system core implying exchange of information not such to raise safety critical issues in the core.
This approach has been chosen with the following motivations:

- Promote the possibility of new technologies insertion in the core.
- Lower testability problems for safety critical functions, facilitating the system certification.
- Avoid the introduction of dedicated safety critical modules in the core, improving standardization.

The above has been interpreted as a recommendation, and has been taken in account during the definition of the architecture proposal, but there is the awareness that things may evolve differently.

6. OVERVIEW OF TECHNOLOGICAL SOLUTIONS ESSENTIAL FOR SYSTEM ARCHITECTURE DEFINITION

The work package dedicated to Technology Studies has absorbed more resources than any other section of the RTP4.1 programme. Scope of this paragraph is to give a short account of those technology solutions which have been more important in defining the proposed avionic system architecture.
Although the architectural study has not addressed packaging (this topic has been thoroughly analyzed by technology studies of RTP4.1), the physical realization of the system core can be synthesized as follows:

- One or more *Racks*, each hosting:
  - Backplane
  - Cooling facilities
  - Power Distribution facilities
  - Line Replaceable Modules (LRMs), fitting in the backplane and inside the rack

- A *Communication System*, which will provide data distribution among the digital elements within the core, and an interface toward the Sensor Areas, the Crew Interface Area and other systems such as Vehicle Control.

For our scope it is necessary to report some essential technological results concerning:

- Modules families
- Networking solutions

6.1 Physical Modules Families - Performances and Characteristics

In order to implement by means of modular units the system elements pertaining to the digital core, reported in para. 4, a general standardization criteria has been taken in account, requiring the minimization of the different types of modules to be realized.
Detailed technological studies have been carried out, including review of currently available technologies, functional partitioning in solid-state devices, packaging solutions, multiprocessing issues, modules functional and physical interfaces, etc. The resulting physical modules, and major characteristics, are briefly summarized in the following, focusing only on those apects strictly relevant for architecture definition.

- <u>Data Processing Module</u>. Featuring a processing capability, indicated in suitable benchmarks, that results compatible with a projected performance of about 2000 MIPS. This is recognized as a poor indicator of processing performance, but is comparable with the above expressed processing requirements. Interfaces: 2 In + 2 Out Data and Control ports. Memory: preliminary module design based on overall 64 Mbytes per module, with grow capability by chip replacement from 100% to 300 %.

- <u>Signal / Image Processing Modules</u>. The need for two kind of signal processing modules is envisaged:
  - <u>General Purpose Signal Processing Modules</u>, performing data dependent algorithms and complex / real matrix operations. Projected processing performance of about 1000 MFLOPS.
  - <u>Special Signal Processing Modules</u>. A dedicated and a general approach have been individuated as possible. As for the system design, the general one has

been taken as reference, having the lower impact on the system size. According to this approach, an Array Processing Module is needed, performing frequency analysis, filtering and correlation algorithms. Projected processing capability: about 4 GFLOPS.

Interfaces: 2 In + 2 Out data ports per module at system level. Other ports are available to realize a dedicated signal processing architecture. 2 In + 2 Out control ports.
Memory: estimated between 64 and 128 Mbytes (overall contained on board).

- Graphic Processing Module. Capable to realize image manipulations like translations, rotations, zooming, dimming, compression / decompressions, etc., images mixing, production of digitized images with resolution up to 2048 x 2048 pixels, 50 Hz refresh rate, bandwidth up to 1.7 Gbit/s. Interfaces: 2 In + 2 Out Data and Control ports.

- Crypto Processing Module. Dedicated to encrypt / decrypt secure communications transmitted / received by the aircraft. It will be specific to the type of encryption used, in order to meet stringent certification requirements. Interfaces: 2 In + 2 Out Data and Control ports.

- Mass memory Module. Dedicated to store huge amount of data, e.g. maintenance data for off line evaluation or digital maps. Projected storage capacity of about 2 Gbytes, achievable in the useful time frame by means of electronic components, featuring more robustness and faster access times than magnetic or optical devices.

- Power Conditioning Modules. The power supply subsystem has been analyzed in detail by technology studies. Here, their presence will be taken in account from a purely functional point of view.

- Network Modules. Treated in the next paragraphs.

6.2 Networking Solutions

It is quite clear that the basic requirement to build the avionic system around a unifying homogeneous network does not cope easily with other requirements, in particular in view of the existence of two basically different classes of information transfers across the system: high rate streaming data transfers (e.g. digitized signals from sensors areas and to the crew interface) and low rate bursty data transfers (e.g.: control information). A single unified network is still to be pursued, but not all of the required technology is today available. The proposed solution realizes a conciliation of opposite demands, presenting a Matrix Switch Network (MSN) concept (see Ref. 3 for a complete treatment of the subject) that combines:

- A primary (circuit switch) network, providing high band point to point optical transmission paths, configurable by means of switching elements. Due to the circuit switch technique, this network is well suited to high rates data transfers requiring the whole bandwidth of the physical links to be available. It will be named in the following MSN Data Transmission Network.
- A secondary network, suitable to carry control / status information and lower rate data transfers, named MSN Control and Message Network.

This networking scheme is briefly represented in Fig. 3. As it can be seen, the central element of the MSN Data Transmission Network is the Link Control Element (LCE), constituted by the Switch Matrix and the Matrix Controller,
The Switch Matrix is to be developed in the long term as a large purely optical array, while a mid-term solution could be to have an electronic switching element and optical / electro / optical conversions. It should be noted how the first solution will drive the choice of the physical media, requiring use of monomode optical fibers
In accordance with the modular approach, it seems interesting to realize the switching elements as modules (and this explains the "Network Modules" recalled in para. 6.1).
A switch matrix size of 32 Input x 32 Output ports is assumed for the LCE implementation, on the basis that this is expected to be the maximum size to be produced in the relevant time scales. A limited number of output ports are configurable for inter-LCE connections. Optical backplanes will be used to carry the circuit switched channels to any LRM requiring high data rate connections.

Primary function of the Control and Message Network is to carry all the signaling and notification information required to establish the MSN dedicated connections. The request for a physical connection is issued by a network subscriber and notified to the Matrix Controller, which, depending also on its current status, reconfigures the Matrix.
As for the realization of the Control and Message Network, a range of possible alternatives has been individuated, all implementing packet switching techniques, Asynchronous Transfer Mode (ATM) being the most promising, followed by Scalable Coherent Interface / Real Time (SCI/RT) and Fiber Distributed Data Interface (FDDI), this last suffering for a disadvantage in granting the low latencies required, due to its ring topology. As for ATM, it results preferable not only due to a weighted requirements analysis, but also for its large and growing commercial diffusion, boosting performances and lowering costs.
ATM networks typically consist of nodes connected in a mesh type topology. Each node controls its outgoing communication lines, and no common access is provided. An ATM network requires its independent switch matrices, and this means that an ATM controlled MSN will use two different types of switch matrices.
Although a preference has been given to ATM, a final choice for the Message and Control Network has not been done.

Finally, it should be noted how, as long term unifying networking solution, ATM

seems to have good chances, due to highly improved performances (e.g. 2.5 Gbit/s data rate) projected for the future.

7. SYSTEM ARCHITECTURE PROPOSAL

The resulting architecture proposal is shown in Fig. 4. A subdivision in a number of areas can be noticed, arranged horizontally in the figure, each integrating an analog block front-end (exception made for area 1), switching network facilities, and an integrated digital processing block (IDPB), hosting the modules. It should be underlined that one IDPB is not to be regarded as one rack, being the architecture, in this sense, at functional (not physical) level. The following considerations will show rationales and features of this architectural model.

The estimates of computing and memory requirements referred to the sensor control processing and mission / system control processing, compared with the technical characteristics of the modules and corrected with general multiprocessing efficiency criteria, yield the number of modules, for each type, required to carry out all the necessary functions, in the absence of failures. Confronting the high overall number of modules, each equipped with 2 In and 2 Out MSN ports, with the availability of LCEs with 32In x 32Out ports, it results hardly feasible to realize a system allowing a connection with the required characteristics to be established between any couple of elements of the system. Schemes could be elaborated to match this full connectivity, cascading a number of LCEs, but they would impact on the system complexity, posing control and latency problems. An attempt to realize an unlimited reconfiguration has therefore be abandoned, in favour of an architecture scheme subdivided in reconfiguration areas, each area being served by LCEs in such a way to allow any interconnection scheme to be established within the area, and to be reconfigured when necessary, not only among the modules of the IDPB, but also between the IDPB and the sensor front-end. The reconfiguration among elements pertaining to different areas will be limited, depending on the available interconnections among LCEs belonging to different areas.
Reconfiguration areas are chosen on the base of close functional bounds, implying necessity for extensive data transfers among elements, and on the base of number of elements required for functional area. Primarily, the following reconfiguration areas have been individuated:

- Mission / System Management and Crew Interface
- Communication / Navigation / Identification (CNI)
- Multimode radar
- Integrated Defensive Aids
- Integrated Electro / Optical

The sensor blocks of CNI, Multimode Radar and Integrated Defensive Aids have been reported as separated in the figure, to point out the different specific functions carried out in the RF domain, but it is well understood that *integration (and modularity) is to be pursued at analog sensor level too, primarily RF, and not be limited to the digital core*. Similarly, *the digital processing of the RF applications tends to be strictly integrated*, as explained in the following.

It is to be noted that the interface toward the sensor front-end can be quite demanding in terms of number of required links, as underlined by some technology studies.

The fault tolerance requirement must be met. To this aim, each area must be equipped, in principle, with 2 redundant modules for each of the needed types of LRMs. As a result, the overall system core will be equipped approximately with the types and number of modules reported in the first row of Tab.3.
The resulting overall number of modules for each area, together with connection requirements toward sensors and actuators front ends, is such to engage more than the interconnection capabilities of 1 LCE for every area, should 2 Input and 2 Output ports per module be connected to the LCE. On the other hand, this LCE must be duplicated to tolerate its fault. In realizing connections between modules and the 2 LCEs, it will be possible to connect each module to both LCEs, using both pairs of I/O ports available on the modules, one per LCE. It can be seen that, with this configuration, a number of LCEs ports are not utilized, their number depending also on the specific implementation of the sensor blocks interfaces. A way of using these ports is to configure them as inter LCE connections among different areas, providing a certain level of reconfiguration among areas. In particular, *this will be done among the areas pertaining to the RF partition, integrating them as far as possible*. Considering also that not all the possible interconnection schemes are necessary, as information flows logically across the system, and not in any possible direction, a sufficient linkage level can then be achieved among IDPBs 2,3,4, such to resemble the existence of *a unique RF digital reconfiguration area*. In this case, less redundant elements will be necessary, as they will not be replicated for IDPB 2,3,4. The resulting approximate overall number of modules for this solution (3 primary reconfiguration areas: Mission/System Management and Crew Interface, Integrated RF, Integrated EO) is reported in the second row of Tab. 3 (for correctness, it should be pointed out that this quantitative evaluation has been made outside the RTP4.1 study).

A couple of LCEs is not yet enough to tolerate a double catastrophic fault at LCEs level. The following solutions can be identified:

- Addition of a third LCE for each area
- Use of not engaged LCEs ports of, e.g., area 2, to provide an alternative route among the sensor block and the modules of, e.g., area 1
- Addition of a spare reconfiguration area, equipped with limited resources

(single redounded), to be substituted to any of the primary areas in case of total fault of any of these areas due to double LCEs failure

The third one is the solution proposed. Although it has the disadvantage of requiring its own set of modules, it utilizes in principle a lower number of LCEs than the first, and should be more easily controllable. The second solution would be no cost, but conditioned by the effective sufficient availability of spare LCEs ports. It should be underlined that the effective necessity to cope with total fails of LCEs will have to be verified when specific data about failure modes and rates of these components will be available. Considering also that the second solution may reveal possible, *the additional spare area should be considered, at the moment, as optional, not part of the basic architecture.*

The control and message network has been outlined quite generally in the figure, as no final choice has been done about its implementation. It will have to be properly redounded.
The outlined architecture satisfies and exceeds, in principle, the fault tolerance requirement. In fact, the fail of any 2 identical elements of the system (event 1 of the fault tolerance requirement) does not degrade performances, as a proper reconfiguration within the same area will allow the exploitment of substitutive resources. Event 2 (fail of a third but different element) results still in no performance loss. The most stringent case is in fact the one for which one area is completely failed due to the failure of two LCEs. In this case the spare area becomes active, equipped with a number of modules integrating a single redundant element for each of the needed types of modules, which allows the overcoming of any single fault.
Further fails of the same type of components (worst case of event 3 of requirement) degrade performances, but only when occurring in the same reconfiguration area. In general, it should be noted that, once the availability of spares is over, reconfiguration schemes can take place among active components also, redistributing tasks among them, obtaining a graceful degradation of performances.

The architecture topology allows the realization of data fusion strategies.
A specific reconfiguration area (Mission Management) has been equipped with resources dedicated for data fusion, and it is possible to supply to this areas pre-processed information, or raw data outcoming from sensor front-ends, depending on which specific strategy of data fusion is requested on the specific phase of the mission. This is done by means of the inter-LCEs connections between the Mission Management area and the various sensor areas interested by data fusion algorithms (see para. 5.2 for requirements).
The implementation of specialized data fusion algorithms in the area dedicated also to crew interface seems advantageous, as the results of image/data fusion require typically an effective interface toward displays, provided in this area by means of an extensive use of graphic processing resources, connected to displays through LCEs. Nevertheless, displays can be driven also by any other area, improving the reliability of the crew interface function.

8. CONCLUSION

The paper has briefly outlined the logical process which, within RTP4.1, has been adopted to define a suitable modular integrated system architecture. The most relevant results and rationales have been reported. Important features of the architectural model have been discussed, as the capability to tolerate faults and performing data fusion at various levels.

It is worth noting how a topic as system architecture definition encompasses software architecture as well. Strong efforts have been carried out in this direction by RTP4.1, but the subject was outside the scope of this paper.

Concluding, the architectural studies herein described cannot claim any conclusive value. Requirements and technological variables are still too many to allow a definitive result to be reached, and, at the same time, experimental activities on laboratory prototypes will have to be carried out.

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3. D. Aupers, S. Wellink and G.J. Heerink, "Simulation of a cell switched network for the control of a switch matrix in a high-speed avionics network", presented at AGARD Mission System Panel 6th Symposium on Advanced Architectures for Aerospace Mission Systems, 14-17 October 1996, Istambul, Turkey.

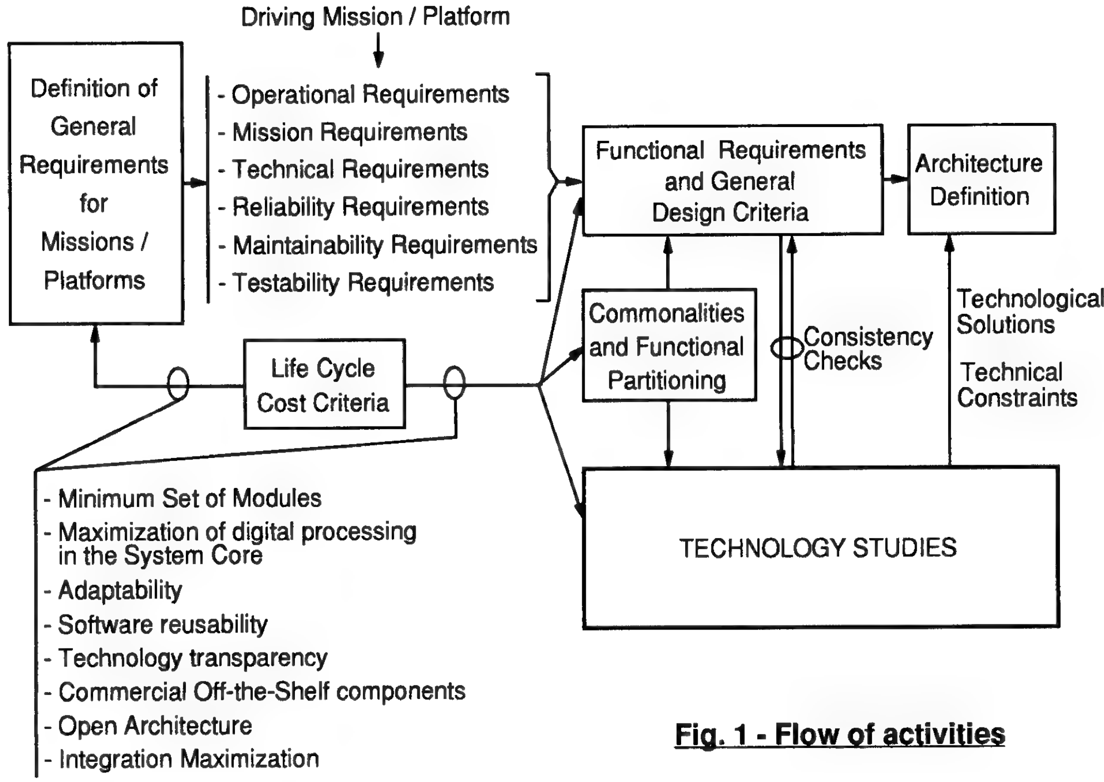

Fig. 1 - Flow of activities

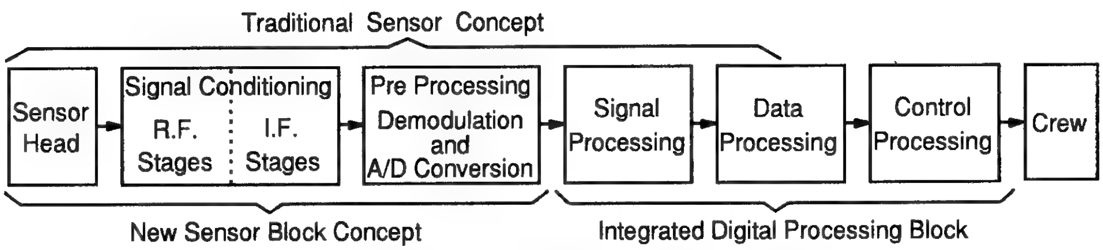

Fig. 2 - Functional chain for generic RF application

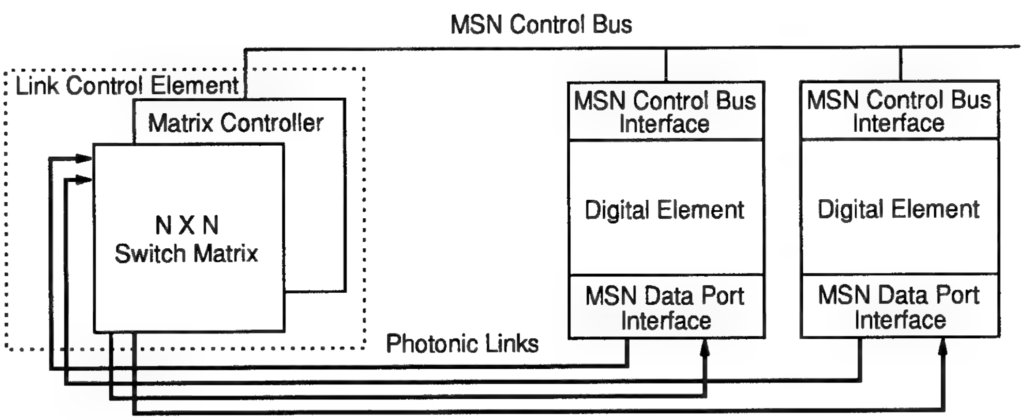

Fig. 3 - Matrix Switch Network scheme

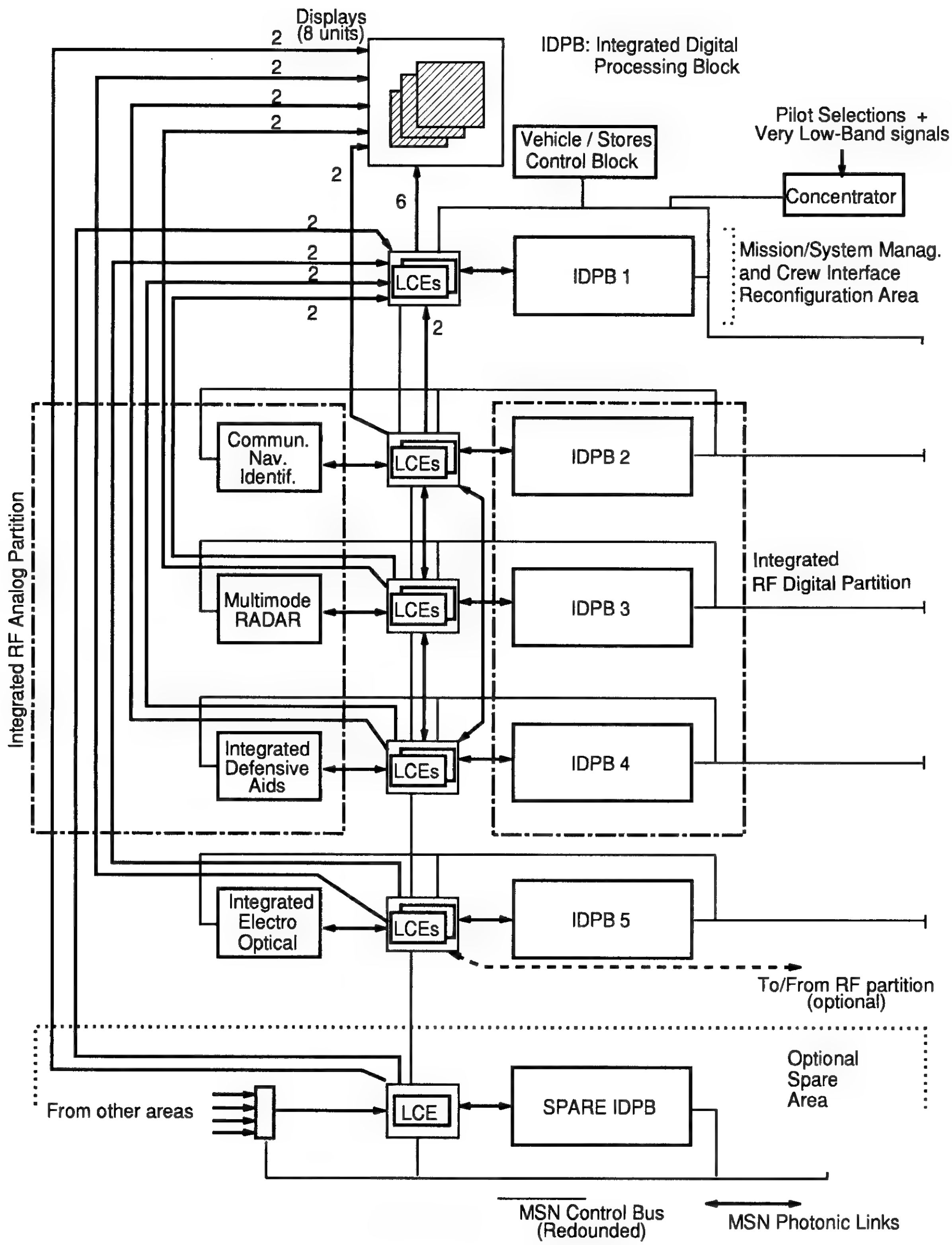

Fig. 4 - General System Architecture

Functional Macro Areas	Subfunctions	Necessary System Elements
Vehicle/Stores Control	• Inlet Control • Propulsion Control • Electrical Power Control • Armament Management Control • Flight Control • ...	Data/Control Processing
Mission/System Control	• Mission Initialization • Navigation / Flight Path Generation • Data / Image Fusion • Image Analysis / Classification • Integrated Diagnostics • System Reconfiguration • ...	Signal/Data/Control Processing
Sensor Control	• Sensor Configuration • Communication Management • Target Detection • ...	Signal/Data/Control Processing
Crew Interface Control	• Image / Map Generation • Crew Selection Acquisition • ...	Data/Control Processing

Table 1 - Functional Partitioning

Sensor	Data Processing (MIPS)	Signal Processing (GFLOPS)	Memory (MByte)	Output Data Rate (Gbit/s)	Iteration Time (msec)
Multimode Radar	500	10.0	100	1.4	1
EO	1000	7.5	40	1.0	40
Integrated Defensive Aids	1200	10.0	200	2.0	1 - 40
CNI	200	3.0	35	3.0	> 25

Table 2 - Sensor Processing and Interface Requirements.

Architectural Solution	Data Processing LRMs	Generic/Specific Signal Processing LRMs	Crypto Processing LRMs	Graphic Processing LRMs	Mass Memory LRMs
5 Reconfiguration Areas	17	41 - 43	3	20	4
3 Reconfiguration Areas	11	33 - 35	3	14	4

Table 3 - Estimated number of processing modules

When Do Advanced Avionics Architectures Make Sense For Upgrading Aging Aircraft?

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Keywords: Aircraft upgrades; avionics; avionic upgrades; avionic architectures; integrated modular avionics.

1. ABSTRACT

With the dramatic reduction in defense spending in NATO countries, it is quite clear that there will be few new military aircraft for perhaps many years. A consequence is that there will be widespread use of current aircraft to satisfy future military mission requirements. One of the most cost-effective means for improving the capability of a military aircraft to deal with new threats and mission requirements is to upgrade the performance of the avionics suite. However, current federated avionics subsystems are weapon-system unique, have limited capability and life and may not support new functional requirements. In addition, the cost of performance upgrades for federated avionic suites are prohibitive, particularly in terms of the budgets available. Integrated, modular avionics technologies offer substantial potential for improving the reliability and reducing the cost/weight/volume per function for adding new functional capability. Integrated, modular avionics are normally considered for new aircraft, but there is some evidence that they may have potential in some circumstances for older aircraft as well. This paper examines several military aircraft applications and discusses the circumstances where the retrofit of an advanced avionics architecture may be preferred to more conventional approaches. The major consideration is cost per function. The paper will show that the advanced architecture is a clear winner as the number of functions is significant in terms of the level of integration required with other subsystems. It is very difficult to determine with even coarse precision the costs of various approaches, but certain trends are apparent. Not too surprisingly, the dominant acquisition cost is not the avionics equipment, but the cost of installing and integrating the equipment into the aircraft together with the cost of testing, documentation and training.

2. SUMMARY

This paper identifies the need to upgrade the aging federated avionic systems on older aircraft with new Integrated Modular Avionics (IMA) architectures that are more capable of meeting the needs of future missions and operations. Aging avionic systems are in need of upgrading due to the increasing problems of obsolescence, poor reliability and the difficulty of modifying old systems to meet new requirements. The benefits of IMA are reduced cost and weight, and increased reliability. IMA will have most benefit in saving organization and support costs and future modification costs whilst saving weight and volume for use by other systems and equipment. The factors which most affect the outcome of studies into the viability of upgrading with new architectures are the total number of aircraft across which the modification costs can be spread, the number, complexity and suitability of the functions selected, the environmental cooling needed, the weight, volume and density of the new architecture and the candidate aircraft's capacity to accommodate the new units. Cost-benefit analyses indicate that IMA can be cost-effective given the right parameters. The Science and Technology community can contribute to the viability by concentrating effort in several areas where IMA could be made even more cost effective. The impact of adopting IMA on the avionic manufacturing base will be significant. IMA presents new challenges and opportunities for the brave whilst allowing more of the available money to be spent on additional functionality.

3. INTRODUCTION

3.1. The United States Air Force has completed many studies into the viability of new avionics architectures with the objective of deciding the way forward for future avionics systems. Based on these studies, the designers of the latest technology fighter aircraft have chosen integrated modular architectures for their avionic systems. More recent studies have sought to identify the most cost-effective method of providing greater functionality and capability to older aircraft.

3.2. The cost of maintaining older avionics systems continues to increase and in some cases they are becoming unsupportable due to the obsolescence of parts and poor reliability. The basic law of supply-and-demand has driven the cost of some items to exorbitant heights. In addition, the continued pressure to provide additional functionality and capability from older systems has stretched federated system technology to its limits. The cost of upgrading old systems or providing them with additional functionality will therefore remain very high. However, at some point this objective would be better met by changing to new architectures which would meet the challenges and provide additional benefits such as the capacity for growth needed to satisfy the operational needs of the foreseeable future. This paper seeks to identify the factors that will influence the point at which it would be viable to use advanced avionics architectures to upgrade federated architecture-based systems on aging aircraft. This paper covers the background to this question, identifies the driving factors behind the need to upgrade aging systems, explains those factors which most affect the viability of upgrading aging systems with advanced architectures, presents some of the science and technology which could affect future decisions and, finally, considers some of the impacts such action could have on the avionic manufacturing base.

3.3. For the purpose of this paper the following terms are defined:

a. **Federated Systems**. Federated systems have their own chain of apertures, sensors, transducers, transmitters, receivers, pre-processors, signal processors and,

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sometimes, their own displays. Some integration might be provided by databuses such as STANAG 3838 (MIL STD 1553B). Each federated system contains resources that are duplicated in other systems and rarely are any used to full capacity all the time. An illustration of a federated system is at Figure 1.

b. **Integrated Modular Avionics (IMA).** Integrated avionics architectures integrate the functions of the systems it covers thereby sharing the available resources and reducing duplication. Thus, in an IMA system, there would be fewer items such as power supplies, boxes, chassis and cabling. Resources, such as processors, are centralized for managed utilization by a control layer of core processing. In most examples the modules are located in one or more racks. IMA can comprise digital data processing, signal processing or both. Figure 2 shows an example of an IMA system.

c. **Distributed Processing Architecture.** Distributed architectures allows sub-systems to process their own data with the main integration computing left to a central computer. However, unlike IMA, distributed processing architectures allows sub-system and main computing elements to be undertaken by any one of a number of the sub-system processing elements. Distributed architectures are therefore thought to be more reliable and resilient to battle damage.

4. BACKGROUND

4.1. Federated systems have proved to be effective pillars of avionics architectures for many years. Indeed, Figure 3 shows the number of Shop Replaceable Unit (SRUs), Line Replaceable Units (LRUs), systems and aircraft types currently being supported by the USAF based on this technology. However, with the demand for more functionality has come new levels of complexity and the need for greater integration. The resulting federated systems, integrated by databuses and hard-wired discreet signals, have become complex challenges for designers, support organizations and maintenance engineers. It is not uncommon for sub-systems of varying complexity and technology employing different levels of hardware and software sophistication to be wired together in a time-critical manner. These systems do not tolerate easily modifications or change in any form. As a result even modest improvements can be difficult or impossible to make without introducing unwanted problems. The demands made of avionics systems are likely to continue to grow necessitating ever more processing power, bandwidth and capacities.

4.2. Researchers and managers of modern aircraft projects currently in design and in production foresee great benefit from new avionics architectures. It is believed by many scientists and engineers that these benefits could be extended to aging aircraft by using architectures identical to those on the latest aircraft thereby reducing the combined overall cost of acquiring and supporting these systems. Further benefits and savings could then accrue from the standardization and commonality that would follow such a strategy.

4.3. Recent investigations in the USAF have sought to identify the value of the proposed benefits of introducing new architectures into aging aircraft. This paper covers the issues of fitting advanced avionics architectures to aging aircraft and identifies the areas any such proposal should consider.

5. THE NEED TO UPGRADE

5.1. The maintenance and support issues of older aircraft are now posing more urgent questions than for new aircraft. The need to upgrade aging aircraft systems stem from one of the following factors:

a. **Obsolescence**. Parts become obsolete for many reasons resulting in the need to find compatible replacements or to modify the system or part thereof. The cost of replacing obsolete parts is well known to maintainers, however, one example typifies the problem. A high performance sunlight-readable cathode-ray tube originally cost less than $200. When the initial spares buy was depleted the original manufacturer was no longer in business. Competitive tendering resulted in the winning contractor manufacturing a years supply at $2,000 each. When this supply was depleted only 1 contractor responded to the invitation to tender and quoted prices in excess of $10,000 each.

b. **Bad Actors**. Poor in-service reliability causes a higher than expected need to replace and repair the item resulting in higher maintenance costs and loss of system availability. Poor reliability of aging avionics items has seen examples of support costs rising by as much as 50% per year.

c. **Performance Upgrades**. The need to undertake more demanding missions, meet new challenges, and counter new threats has resulted in the continuous review of proposed performance upgrades to aircraft and their systems. As complex systems with increased data requirements and capabilities are introduced, the need for architectures beyond traditional federated systems grows more necessary. Many systems of the future will require much greater bandwidth and speed for their full potential to be realized. Simply adding more databuses is insufficient, impractical and wasteful. A new architecture, such as IMA, is a necessity to host such systems.

5.2. It is difficult to determine precisely how much money is spent addressing any one of the above categories as, in practice, modifications tend to be bundled together as part of a single program which addresses several issues at the same time. However, performance upgrades are continuously under review for most aircraft but are frequently rejected due to a lack of sufficient funds. Bad actors are more prevalent with aircraft in the early and late stages of their service life and are a growing concern to those responsible for maintaining aging aircraft. Obsolescence is a growing problem aggravated by the rapid development of new products in the commercial market leading to shorter availability lives and by keeping older aircraft in service for longer than originally envisaged.

5.3. As the cost of maintaining and supporting aging systems continues to increase there must come a time when two decisions have to be made. The first decision is whether to upgrade the system or continue to suffer the costs and limitations of aging systems. The second decision is whether to upgrade the old federated architecture with more of the same or to strive to take the advantage and introduce new architectures that will give the aircraft greater capability and the maintenance organization greater flexibility to meet the challenges of the future. For most air forces, regardless of the

perceived advantages, any new solution must be proved cost-effective over the remaining life-cycle of the weapon system.

5.4. The largest single cost of significant avionic upgrades is often that for Group A costs. Group A costs are all those costs incurred in providing the installation and location on the aircraft excluding the cost of the modified equipment itself. The need for new wiring, structural modification and software rewrites can obviate all but the most essential upgrades. In one example, equipment costing less than $150k per aircraft was to be fitted to 10 aircraft. The Group A costs totaled more than $5M. Another, non-structural modification, sought to fit a $10k electronic unit. Group A costs were in excess of $75k per aircraft. In some countries the virtual monopoly enjoyed by contractors with sole design authority rights reduces the possibility of competing the installation and Group A costs become an even greater obstacle.

6. WHEN DOES IMA MAKE SENSE?

6.1. The USAF has undertaken cost-benefit analysis investigations into identifying the costs associated with introducing IMA into aging aircraft and to determine the point where the new architectures become viable compared to traditional federated architectures. The issues and general conclusions are of value to all air forces considering undertaking similar investigations.

6.2. **Cost-Benefit Analysis (CBA).** For most organizations the decision process requires completion of a comprehensive CBA showing the cost effectiveness of the various approaches being considered. Upgrading a single federated system would almost certainly provide no cost-effective alternative but to upgrade it with a similar federated system. However, as shown in Figure 5, as the number of avionic units to be upgraded and additional requirements, functionality, capability, and integration are added, the benefits of new architectures become more affordable. For example, when upgrading a radar system electronic unit, the most cost-effective strategy would normally be to replace it with a new federated electronic unit. But when upgrading an entire communications suite and adding new functions and capabilities to the requirement, new architectures become more viable. Providing basic disparate systems with no common functions or requirements would probably not prove viable, whereas, providing several computing-intensive communications, navigation and identification functions would probably be worthy of close analysis. It is essential that the CBA compares like with like. It is not correct, as some have tried, to compare modern IMA upgrades with upgrades based on old federated architectures. The benefits and costs of new IMA upgrades must be compared to new federated upgrades. Thus the advantages of open architectures, standardization and commercialization are equally applicable to both cases. Accurate reliability and maintainability data must be intelligently used to arrive at a logical conclusion. The use of extraordinary data such as that from Operation Desert Storm should be used with caution as such data is tainted by environmental and operational peculiarities.

6.3. **The Benefits of IMA**. The benefits of IMA can be summarized under three headings: Cost, Weight and Volume, and Reliability.

6.3.1. **Cost.** The objective of IMA development has always been to reduce the future costs of avionic architectures. Figure 4 shows how the future overall cost of avionic architectures should be reduced by the adoption of IMA, and how organization and support costs should be reduced by the greatest proportion. The overall cost of the modification will vary widely between different air forces due to different ways of doing business. The following examples are representative of the results from various studies and cover the main categories of cost.

a. **Engineering & Manufacturing Development (EMD) Cost.** EMD follows Demonstration and Validation of a modification and includes the costs associated with prototype production, testing and trial installation. EMD costs for an IMA based architecture were found to be similar to those of federated systems except in cases where some of the EMD cost had already been paid by other upgrade programs. In these cases, EMD costs were half those of comparable federated systems. EMD costs represented less than 5% of the total life-cycle cost of the modified system.

b. **Production & Deployment (P&D) Cost.** P&D comprises production of the modification kits (Group A and/or Group B), delivery, installation and disposal. Total P&D cost was found to be similar for both IMA and federated architectures. These costs accounted for approximately 85% of the modified system's total life-cycle cost.

c. **Organization & Support (O&S) Costs.** Determining O&S costs was particularly difficult due to the many unknowns which could not be resolved until actual manufacturing had been started. Nevertheless, total O&S costs were found to account for less than 10% of the overall project life-cycle cost of the modification. It was most important during this stage to remember that the studies had to compare standardized and open IMA architectures with standardized and open federated architectures also of the latest technology.

d. **Future Modification Costs.** Future operational requirements and cost reductions are as hard as ever to predict. In addition, there are many uncertainties surrounding future missions and the threats to be faced. IMA systems offer some solutions to supportability issues primarily because future upgrades should be cheaper and easier to embody. Figure 5 illustrates that even when the life-cycle cost study indicates that IMA will not be particularly beneficial, the significantly reduced cost of future upgrades can make a great difference to the viability of the upgrade. This benefit is based on the fact that much of the IMA hardware and software is accessible and reconfigurable and could, therefore, in some cases be utilized to provide all or part of the new capability. As more information intensive functions such as combat identification, target recognition and battlefield management are demanded, the value of central processing becomes more apparent. Obtaining raw, processed, or corroborative data from an integrated system would be faster, easier, and cheaper than establishing a similar capability from dispersed federated systems. If available, using spare capacity in the IMA rack would be less costly than fitting a new black-box federated unit. It has been demonstrated that for some modifications complex new functions or capabilities could be provided by modification to the software alone. One recent study illustrated the

savings achievable with IMA systems. The study showed the total cost of introducing one new communications function to an aircraft with a modern federated solution would cost $92k per aircraft. To introduce that same capability as an integral part of an existing IMA system would cost only $53k per aircraft. Furthermore, a new function (TACAN) was provided at almost no additional cost, allowing the old system to be removed to save weight and provide space. In addition, the O&S cost of supporting the federated system was calculated to be $47k per aircraft whereas the IMA solution would cost just over $4k per aircraft. Many additional examples of substantial savings show that once the up-front cost had been paid the future costs of maintenance and modification could be substantially reduced.

6.3.2. **Weight and Volume.** The weight saving of IMA systems depends on many factors not least of which would result from any need to provide liquid cooling. As electronics become more compact the problem of dissipating the higher temperatures becomes more pressing. Providing any kind of cooling on aircraft is expensive and an unwelcome maintenance penalty. High operating temperatures decrease reliability. In comparing architectures, it was shown that IMA had a density approaching 1,000 kg/m^3. IMA equipment racks could therefore weigh significantly more than their federated counterparts and may require structural modification to the host aircraft to support the additional weight over the design envelope. Equivalent federated systems would have lower densities and greater weight due to the larger number of parts, boxes, connectors and wiring.

6.3.3. **Reliability.** Many design aspects of IMA indicate a much greater reliability than federated architectures. The ability to reconfigure IMA architectures using software means that any under-utilized asset could perform the function required thereby maximizing efficiency and enabling continued operation following failures. By modeling the varying demands of the different phases of flight and missions the optimal utilization of each asset can be determined. Fewer modules are required as the utilization rate of the resources available is much higher. IMA systems, therefore, have fewer unique parts.

6.4. **Key Factors.** The factors which most affected the outcome of the studies and should therefore, be carefully considered before undertaking similar studies, were as follows:

a. **Number of aircraft and aircraft types.** Across how many aircraft and aircraft types could the costs of modification be spread? The same architecture could be fitted to a variety of different aircraft giving commonality across fleets. Not all aircraft need to have all functions.

b. **Number of functions, technical sophistication and complexity.** Choosing systems with common functionality enables the greatest benefit of reconfigurability to be maximized. The more functions to be upgraded the greater the viability. Sophisticated and complex functions can provide less demanding functionality at little additional cost by utilizing spare capacity. Selecting basic avionics functions would limit the benefits of the new architecture.

c. **Environmental requirements.** Although federated systems normally require some kind of air cooling, IMA systems can be so densely packed as to require liquid cooling. Providing even limited liquid cooling is a major cost and engineering concern that can make even the most viable new architecture unaffordable. The need for liquid cooling should therefore be avoided if possible.

d. **Weight, volume, and density**. New electronic modules mounted in racks significantly reduce the overall volume taken up by avionics systems. However, this increased density can overstress the structure in the area traditionally used to house avionics. Strengthening the structure, if required, can be prohibitively expensive as this alone can exceed the total cost of the program.

e. **Single or multiple racks.** Integrating all the electronics into one small package may not be physically possible due to a lack of space. It is possible to use more than one rack, but as the number increases the dependence on the reliability and integrity of high-speed interconnects increases and this adversely affects reliability. Using more than one rack could also lead to interesting problems for calculating the reliability of modules which might be fitted in several different locations during their lifetime. For example, calculating the predicted reliability for a module that might spend some of its life in the nose of an F-15 and some above an engine in an F-16 could be complicated due to the effects of the different environments. The physical problems of introducing IMA racks into small fighter aircraft are significant and could prove to be prohibitively expensive.

6.5. Whilst the outcome of any analysis would be most affected by the above factors the selection of functions would be of paramount importance. Figure 6 shows 2 cases studied. The first case considered integrating systems not suited to IMA as they had little functionality in common and the airframe was a small fighter. The second case considered systems which could share resources and the airframe was suitable for accepting the IMA rack. The point at which the crossover occurs will depend on all of the foregoing factors.

6.6. **Software**. Estimating the cost of initially providing and then maintaining software for both IMA and federated systems is difficult because of the need to define the system in detail before an accurate guess can be made of the software functionality required. Due to the complexity of IMA software and its software control of all the available assets, it would probably prove more expensive to develop. However, IMA could unleash the real power of software as all data and resources would be accessible to the controller. With this extra power comes greater burdens in integration and testing. Research shows that software changes are made at a rate of about 10% per year. Of these changes: 5-10% are corrective in nature (fixing bugs); 30-40% are needed to adapt the software to take account of new hardware; and 50-60% are changes to introduce modifications and improvements. The maintenance and support of software once provided is likely to be very similar for either IMA or federated systems.

7. WHAT ARE THE SCIENCE AND TECHNOLOGY DEVELOPMENTS WHICH COULD MAKE A SIGNIFICANT IMPACT ON AVIONICS UPGRADES?

7.1. **Electronics packaging and cooling technology.** The manner by which electronics are packaged and cooled plays a crucial role in upgrading aging aircraft avionics as this

technology determines the weight, cost, reliability, and performance of the installed avionics. Indeed, this subject was of sufficient importance that the AGARD Avionics Panel devoted an entire symposium to the subject in 1994 (Ref 1). The subject is so important because there is an enormous amount of relatively low cost electronics technology which could be used for airborne applications if the technology could be packaged and cooled to withstand the severe temperature and vibration environments found on airborne platforms. Invariably, the measures taken to protect the electronics result in exorbitant increases in cost and/or dramatically reduced performance. In that the processing speed of the subsystems using microprocessor chips requires their close proximity to minimize transmission time, it is readily apparent that severe cooling problems can result from the use of large quantities of these high performance chips in the close confines of tactical aircraft. The Semiconductor Industry Association (Ref 2) projects a 400% improvement in the on-chip clock performance of high performance chips over the next 15 years. Over the same period of time, the cost per transistor will decrease by 500% and the heat to be dissipated in the heat sinks for these high performance chips will increase from 80 to 180 watts per chip. Air cooled avionics can generally tolerate 40-70 watts heat dissipation for each Standard Electronic Module size E (SEM-E). As we can easily fit 10 or more chips on a SEM-E module, we approach 1 kilowatt dissipation with today's commercial off the shelf (COTS) technology. So the science and technology problem is how to make use of relatively inexpensive and very high performance chips on tactical fighter aircraft without using heavy and costly cooling systems. Another tact, is the development of light weight, low cost, high reliability electronics cooling concepts. Work on heat pumps may prove satisfactory for at least small cooling loads (e.g., 1-2 kW).

7.2. **High temperature semiconductor technology.** The high heat dissipation anticipated with high performance CMOS processing chips poses a severe packaging and cooling problem as mentioned above. The junction temperatures for these transistors must be kept below 120^{O}C. One solution is to use higher temperature semiconductor devices. Silicon on insulator (SOI) technology will withstand 250^{0}C temperatures and silicon carbide devices will withstand 400^{0}C junction temperatures. However, any solution will be enormously expensive to realize as many new materials and manufacturing processes must be developed. The investments required will only result if it is found that such devices are of commercial interest and that does not appear likely in the foreseeable future.

7.3. **Low Power Electronics.** Another technology offering promise for reducing heat is the activity under the general heading of low power electronics. The United States Defense Advanced Research Projects Agency (DARPA) (Ref 3) has initiated a series of efforts to develop a new class of electronic systems which dissipate less than 1% of the power of current systems without a performance penalty. The problem of power dissipation is quickly becoming a critical issue for military and commercial products. In the commercial sector, the demand for portable products generally requires that the product dissipate less than 5W because of battery and cooling problems. Similarly, desktop PCs dissipating more than about 30W pose difficult problems because of the expense of cooling and packaging. The program addresses five technology areas including silicon-on-insulator (SOI) substrates, new device structures, manufacturing processes for low voltage circuits, architectures for low voltage circuits, and application demonstrations.

7.4. **Upgraded STANAG 3838 (MIL STD 1553) data bus.** MIL STD 1553 data buses have proven to very successful for airborne applications and have been installed on a wide variety of military and commercial aircraft. As we now consider how to upgrade the avionics systems on these aging aircraft, it is invariably found that increased bandwidth and data rates are needed between the major units of the avionics system. As pointed out elsewhere in this paper, it is extremely costly, and perhaps impossible in some circumstances, to install additional cables for the needed performance. It may be possible to develop technology which would permit the use of installed twisted pair cables for transmitting much greater data rates - perhaps as much as 100 times the 1 MHz data rates for which these cables were originally designed. A new protocol would be needed together with the implementing electronics, but the fact that these cables are installed in so many aircraft and the enormous cost of new cable installation could make this a viable solution for at least some applications. Many challenging technology problems must be resolved including the signal loss through the cables and the electromagnetic compatibility problems which may result from signal radiation from these cables.

7.5. Another technology problem which could prove to be a major factor for upgrading avionics is the notion of bridges between MIL STD 1553 data buses and higher performance buses in development today and in the future. It appears that programmable interface modules (perhaps field programmable gate arrays (FPGA)) which could be programmed to interface the installed MIL STD 1553 data bus with a wide variety of other data buses could simplify the integration of new technology with the older installed technology.

7.6. **Analog to digital (A/D) converters.** Digitization of electronic systems is very effective in reducing the cost and size of avionics as well as improving performance and reliability. The single most critical impediment to increased digitization is A/D converter technology. As rapidly as A/D converters can be improved with respect to bandwidth, resolution and cost, they will be applied to avionics applications. Current technology will permit the 1998 operational deployment of A/D converters with 12 bit resolution, 120 mega samples per second (MS/s) for direct sampling at second IF frequencies of 60 MHz. Direct sampling at 200 MHz (12 bits, 120 MS/s, 120 MHz bandwidth) should be possible by the year 2000. This technology, together with commercial microwave monolithic integrated circuit (MMIC) RF and IF circuits will enable substantial cost, weight, and size reductions in avionics subsystems. For example, technology is currently available to support the development of a radar receiver channel which will fit on one SEM-E size card, will dissipate approximately 70 watts of power, and will cost approximately $15,000. Two of these cards will replace two 50 pound boxes in modern jet fighters.

7.7. **Software reuse technology**. With the dramatic shift to digital avionics for new and upgrade applications, there is and will continue to be profound implications on the development of software for the systems. The single largest impediment to accomplishing an avionics upgrade is often the cost of rewriting, testing and integrating the old software for the new computer. Unless this cost can be dramatically reduced, many

avionics upgrade programs will not get beyond the point of being just an interesting idea. Many military avionics systems introduced into operation in the 1970's and 1980's used the MIL STD 1750A instruction set architecture to minimize the logistic impact of supporting numerous systems. Most of the software was programmed in assembly language or MIL STD 1589 (JOVIAL). However, MIL STD 1750A permitted user defined input /output (I/O) structures. As a result, each computer system has a unique software interface compounding the problem of finding common, low cost solutions. When trying to avoid rewriting all new software, alternative approaches for reusing the existing software generally fall into three general categories. The most expensive and most comprehensive approach is to re-engineer (Ref 4) the old code into a new higher order language (HOL) using, where possible, automated software translators and documentation tools. The advantages of this approach include the fact that the end product is a new software system written in a modern programming language and new documentation. Another advantage is that needed code upgrades can be readily incorporated in the new system. Disadvantages include the need to test and validate the entire software system. This is a very expensive activity that few programs can afford. The least expensive approach involves the use of hardware or software emulators to rehost the old software in a new processor. This approach is not very efficient relative to using the new processor and makes no improvement in the old code. However, it is a relatively inexpensive and quick solution. An intermediate approach in terms of cost and flexibility is the notion of a "software wrapper". In the new processor, an object oriented programming language is used and the old software system is "wrapped" by additional interface software. The legacy software is simply treated as an object in the new software architecture. Science and technology development is needed in all three approaches, particularly software reengineering and software wrappers. Particular attention needs to be focused on software errors by providing adequate fault tolerance to assure that errors do not result in mission failures.

7.8. **Plug and play capability.** The "plug and play" feature available from the Microsoft ® Windows® 95 operating system for personal computers is an intriguing concept to consider for avionics applications. Imagine the cost impact of simply plugging a new module - say an improved Global Positioning System receiver - into an avionics rack and being automatically hardware and software compatible with the installed system.

7.9. **Simulation and modeling technology.** Simulation and modeling technology will play a major role in the development of avionics upgrades (as well as avionics systems for new aircraft). High fidelity simulation models are becoming available which will permit the economical and rapid evaluation of many design approaches to select the correct solution. These models will facilitate the development, integration and testing of software prior to expensive fabrication of the hardware. The VHSIC High Order Design Language (VHDL) (Ref 5) will permit the specification of all essential technical aspects of electronic circuits and thus permit the re-manufacture of obsolete parts in current technology.

8. IMPACTS ON AVIONICS MANUFACTURING BASE

Without doubt, the IMA concept will have a significant impact on the avionics industrial base. Manufacturers who have traditionally developed specific systems or subsystems such as radar, electronic warfare, communications, and navigation now find that the avionics suite of future aircraft and perhaps modifications to avionics on aging aircraft, will be built around architectures which are functionally independent. In the limit, it is entirely possible to consider avionics suites where the functional uniqueness of an avionics suite will only be evident in the software which controls the system. All hardware attributes of the system may be multi-functional in nature and time-shared between the many functions which the avionics is required to perform. These changes will have a profound impact on avionics manufactures who are specialized in avionics subsystems for specific functions. This is a cause for anxiety and optimism depending on your point of view. The IMA paradigm will certainly create many opportunities and needs for new products. These products will provide significant new improvements in avionics functionality while reducing the cost per function. These changes are occurring in a period of time where defense budgets are shrinking dramatically and thereby reducing the opportunities for military procurements of all kinds, including new or upgraded avionics suites. Avionics is unique in the measure of performance upgrade per dollar which can be achieved using modern electronics technology. However, in order to realize the enormous potential of integrated approaches for achieving greater performance per dollar and per unit volume and weight, a new planning paradigm must be used for avionic upgrades. A broader look across all of the traditionally unique avionic functions must be taken relative to upgrading performance or dealing with obsolescence and bad actors. The needs of the entire fleet must be considered to take full advantage of the economies of scale and reduced costs which result from a fewer number of common parts. The current notion that most of the avionics are unique must be upgraded as if unique, must be abandoned. However, even with the performance per dollar advantage that avionics technology enjoys over other technologies (structural, propulsion, materials, etc.) which may be applied to extend the useful service of aging aircraft, a change in design approach must be found to reduce the high cost of avionics upgrades. Cost estimates for many essential avionics upgrades are prohibitive and simply will not be accomplished. This indeed will have a profound impact on the avionics industrial base!

9. CONCLUSIONS

The dramatic reduction in defense spending in NATO countries will result in fewer new military aircraft. Currently fielded avionic systems will need to remain in service for longer than originally envisaged. Existing systems suffer from the obsolescence of spare parts, poor reliability and difficulty in upgrading due to their architecture and complexity. The advantages of IMA offers the opportunity of overcoming the limitations of current systems whilst providing growth capacity and performance to meet future unforeseen requirements. IMA can be cost effective provided the right factors are considered. Selecting functions with similar functionality requirements produces the most viable case for IMA. IMA can be cheaper to modify than alternative architectures. The Science and Technology community could directly influence the viability of advanced architectures by pursuing advances in several critical areas including software, backplanes, packaging and cooling. IMA provides challenges and opportunities for the avionics manufacturing base. It will also provide rewards for successful companies.

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11. ILLUSTRATIONS

12. ACKNOWLEDGMENTS

The authors acknowledge with gratitude the valuable contributions made by Mr David R. Morgan and Mr Mark E. Minges both of Wright Laboratory, USAF.

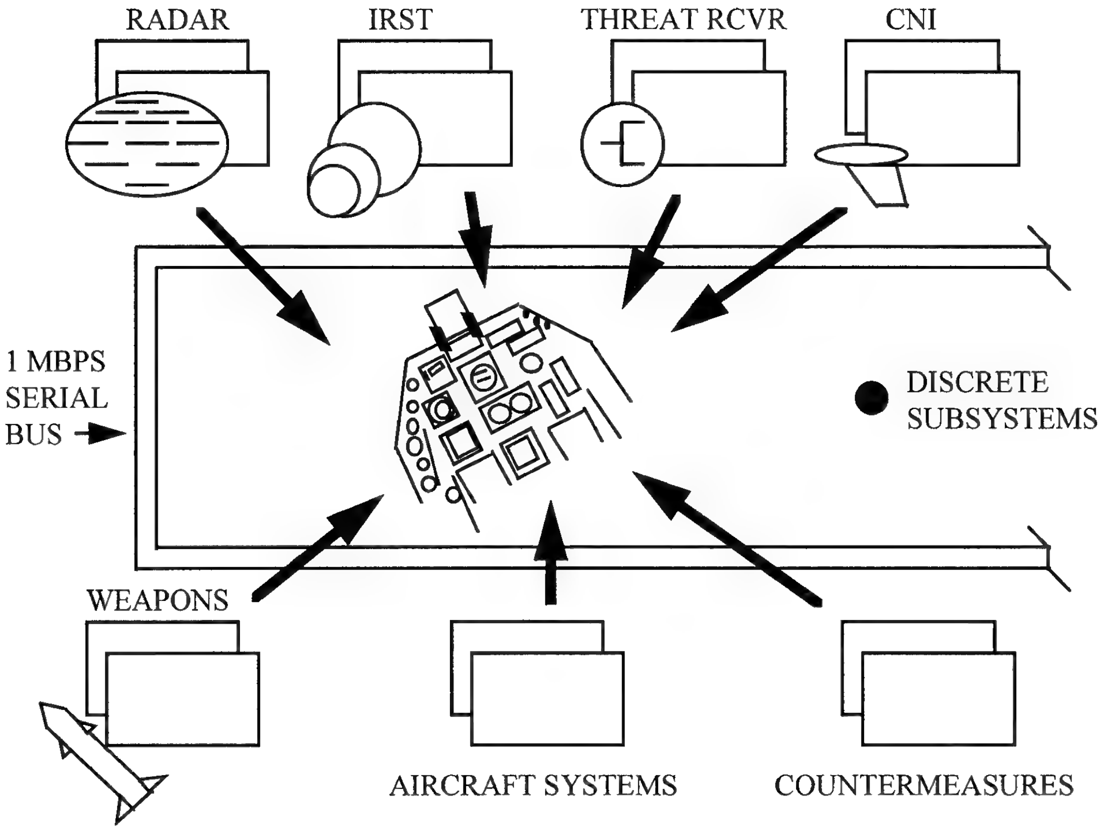

Figure 1. Example of a Federated Avionic System

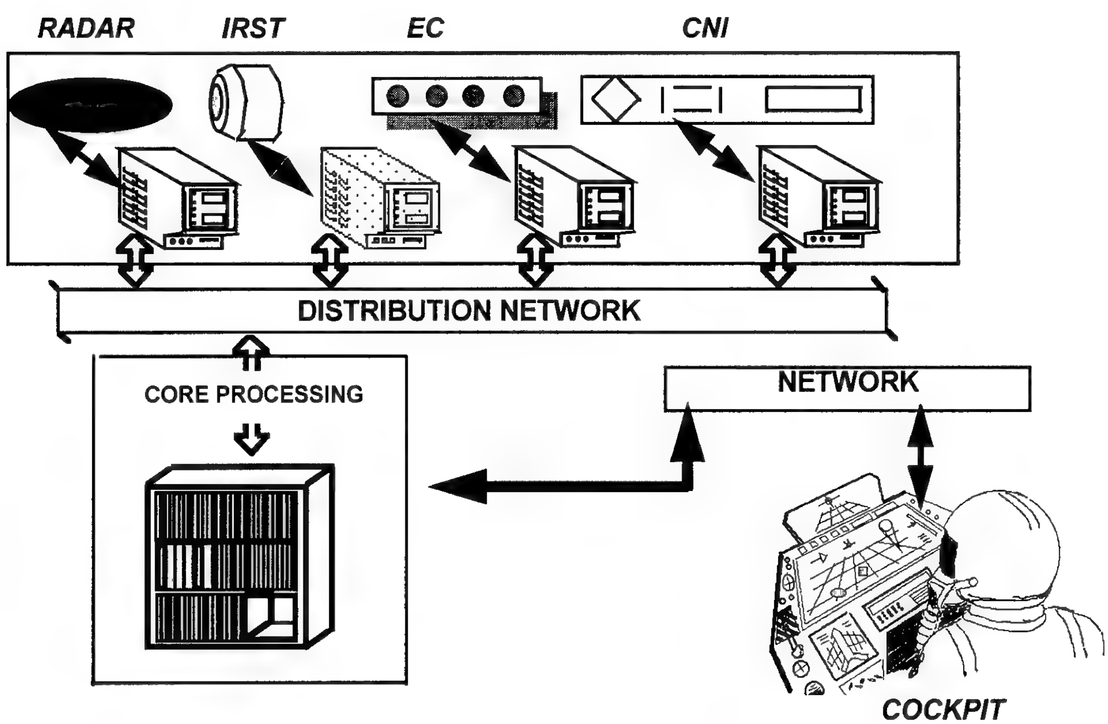

Figure 2. Example of an Integrated Avionic System

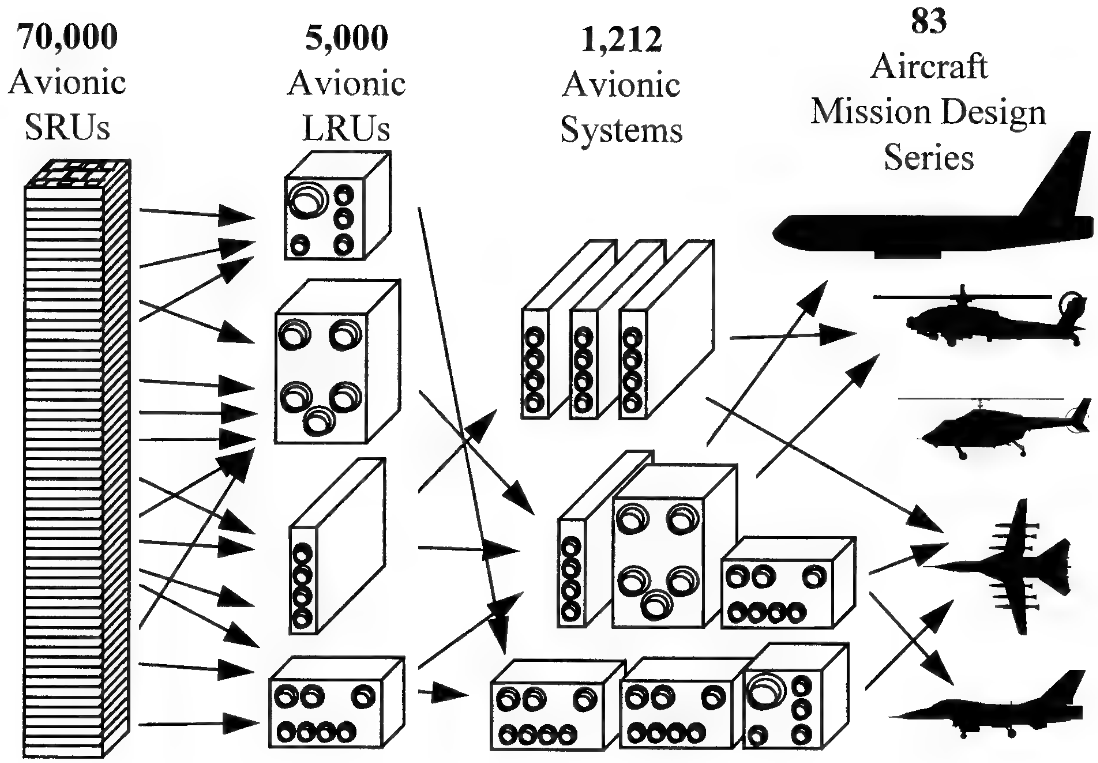

Figure 3. Avionic SRUs, LRUs, Systems and Aircraft

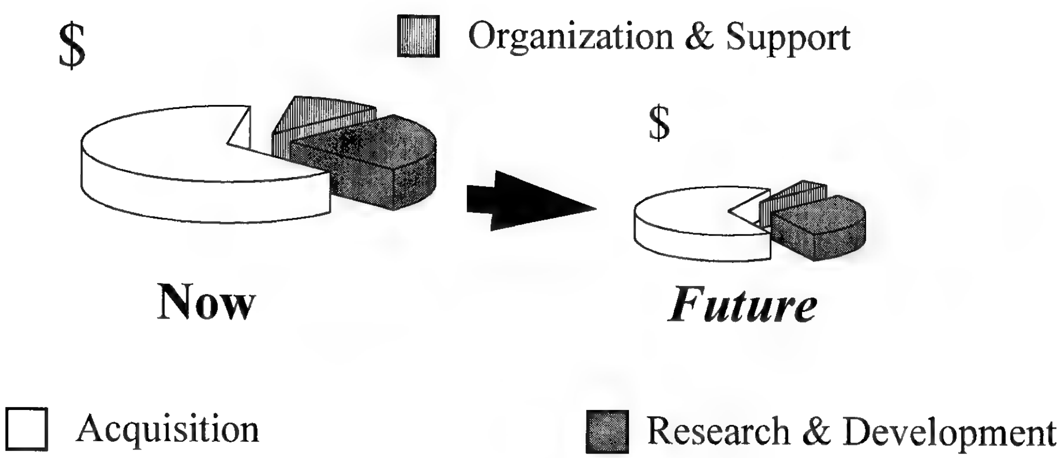

Figure 4. Chart Showing Representative Cost Benefit Analysis Results

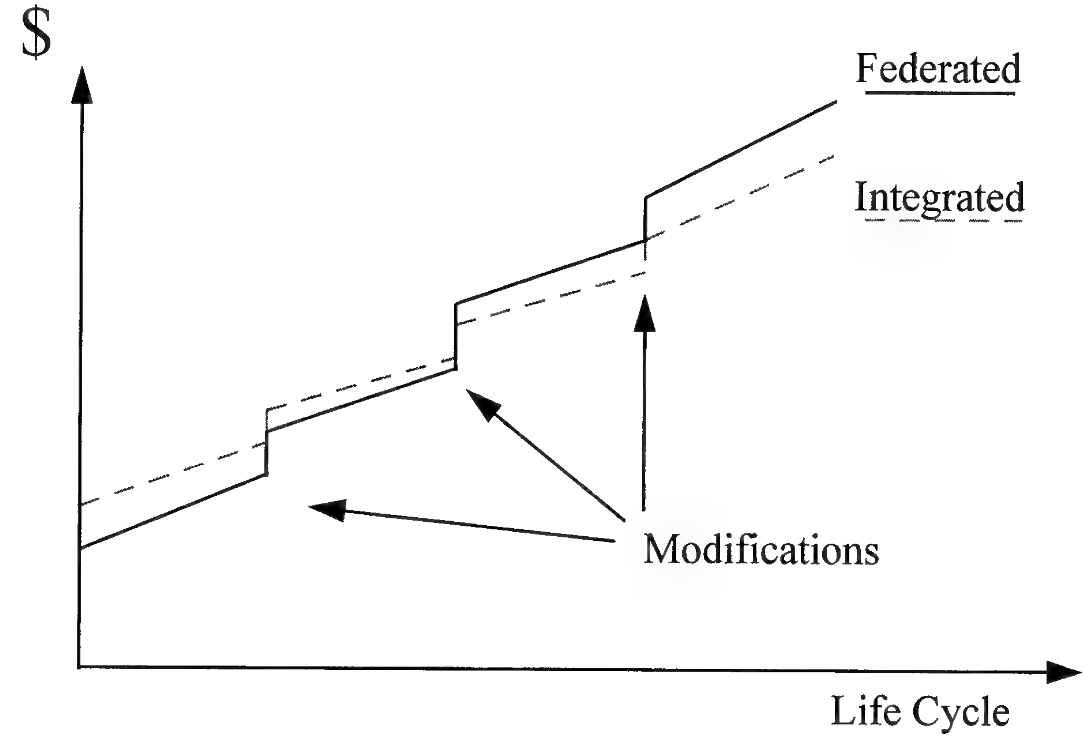

Figure 5. Chart Showing Effect of Upgrade Cost Over Life Cycle

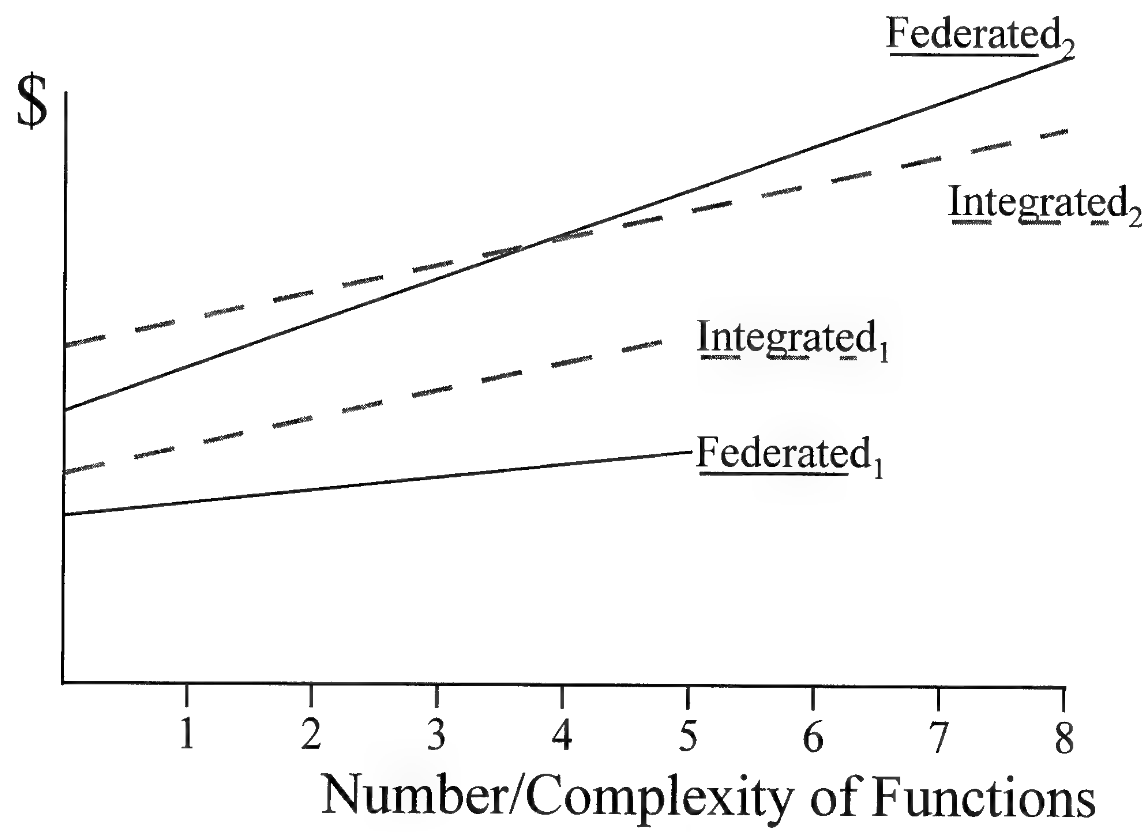

Figure 6. Chart Showing Cost Benefit of IMA

THE FUTURE OF AVIONICS ARCHITECTURES

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SUMMARY

A look into the future of avionic architectures over the next twenty years is presented by extrapolating past evolutionary trends, projecting future military needs and projecting the availability of advanced architectural building blocks.

The basis for this forecast is drawn from the hypotheses that: 1) the physical and functional attributes of architectures evolve, even though the building block technologies often undergo revolutionary changes; hence, extrapolation of past architectural trends provides a good "first cut" look at the future, 2) basic changes in architecture are driven by network bottlenecks resulting from the application of advanced technology building blocks that are used to improve situation awareness; hence an understanding of forces driving improvements in situation awareness and what devices future architects will have at their disposal helps frame the processing and interconnect requirements (and hence the architecture) and 3) cost containment, even cost reduction of avionics systems, will be the dominant driver for future architectures; hence, any form of physical or functional integration that reduces cost also helps define future architectures.

Conclusions drawn from this paper are: 1) architecture changes resulting from avionics updates will continue to be evolutionary, with new building blocks and network designs "grown onto" the existing infrastructure, 2) architectural extensions for retrofits will take the form of "bridging" network interface circuitry that will interconnect advanced COTS-based networks and processors, 3) the drive for improved situation awareness will force architectures to increasingly support signal processor-based networks that will be dominated by several gigabit/second streaming data; as a result, switch-based, point-to-point links will be the primary means of system-level interconnections, with bus-based networks being used mostly for control and message passing at the backplane level, 4) for the first time, the application of new photonics-based building blocks to new avionics designs will eventually allow the avionics architect the design freedom to physically and functionally locate computing assets at space-available locations without performance penalty, 5) highly digital, "functionally integrated, physically distributed" systems will emerge, with the co-habitation of RF analog and digital pre-processing, signal and data processing modules existing within the same module-based enclosure. A physically distributed, unified network will result, with a unified interconnect network across RF, IF, data and signal processing modules, 6) analog photonics will emerge to challenge RF electrical signal distribution, filtering and frequency conversion functions, 7) the digital boundary will move closer to the RF apertures; digital CNI (up to 2 Ghz) systems and a mostly digital-based radar warning and radar systems will eventually replace more costly analog designs, 8) within the next 15-20 years, a new "fourth generation" architecture will emerge that will embody the features described above. The dominant feature of this projected architecture is the similar interconnect structure that both analog and digital avionics will assume. As a result of the increasing digitization of analog functions and the availability of high speed networks, the classical physical boundaries of avionics will almost vanish., 9) architectures will be driven and constrained by the mandate that designs be made open and commercial-based to the greatest extent possible. This trend will profoundly affect future architectures in that network protocols, processors and software operating systems will likely change with time. Coping with this changing environment will require the expanded use of design tools, descriptive design languages and programmable interfaces. Furture architectures must be designed for change at the outset.

1 INTRODUCTION

Predicting the future a avionics architectures requires many assumptions about the direction of military priorities and missions, budgetary constraints and the availability of both commercial and military-unique building blocks. More importantly however is the realization that architectures evolve and hence, are predictable to the extent that an understanding of cause and effect can be achieved. That is, a future architecture "end state" resulting from any projection must be consistent with predictions resulting from an extrapolation of past architectural trends, modified to the extent that the controlling influences can be predicted to change. These major controlling influences will first be discussed and then overlayed onto the motivating reasons why architectures have changed in the past. Coupling this analysis with the availability of system building blocks, the resulting architectures will be predicted.

This paper assumes the following pervasive trends and logically-derived implications will drive future architectures:

1) Mission Needs: The author believes that future avionics suites will continue to be enhanced by off-board sources of

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information in order to improve real-time situation awareness against mobile threats and targets. Another projected mission need is the long-time support of avionics in an austere base environment. *Implications:* The so-called "Information Warfare Era" will eventually have profound effects on the way sensor systems are architected. Avionic architectures will be viewed as a node in a much larger global or theatre-level real-time network architecture. This nodal architecture will need to receive off-board targeting or sensory data and then fuse/integrate this information with on-board assets. (Similarly, this node may be called on to transmit requested information onto the global network) Off-board information must be viewed as if it were derived from a collection of virtual on-board sensors. However, due to the diversity of off-board information and the unpredictability of its availability for a given theatre of operation, the architecture must be extremely flexible in its ability to expand or contract its processing and data distribution tasks. Similarly, mission-custom palletized avionics are projected to become more commonly used in the future and will require extreme architecture flexibility. In addition, the growing need for affordable real-time situation awareness and the move to digitizing RF functions closer to the aperture will increasingly lead to "sensor-system driven" architectures, similar to digital processor architectures. These systems will be characterized by multi-gigabit per second networks that interconnect streaming data between sensor and processing assets using switches. Finally, the other major mission emphasis area that is expected to drive architectures, that of increased sortie generation from austere bases implies that future avionics architectures will be required to support system-level on-board testing and fault-tolerant reconfigurability to allow system performance to gracefully degrade until maintenance actions can be taken.

2) Cost containment. The linear increase in the percentage fly-away cost of avionics since the 1960s has reached the 30-40% level for fighter aircraft. Support costs have followed a similar trend. Sensors account for about two-thirds of the cost, with processors and networks being about 20% and controls/displays, stores management and vehicle management functions accounting for only about 4-6% each. It would appear that this trend is non-supportable and must be halted. One approach currently being pursued to lower avionics cost is to to use commercial off the shelf (COTS) hardware and software to the maximum degree practicable and to reduce the use of unnecessary military standards in favor of lower cost "Best Commercial Practices". This movement for lower cost avionics has resulted in a new US Department of Defense Initiative to pursue the adoption of Open System Architectures. Under this Initiative, commercial industry standards are used to describe the attributes of the architecture so that open, non-proprietary information can be used to promote competition and enable the use of COTS building blocks in order to reduce cost. Further, various programs are underway to reduce sensor costs though the use of multi-function hardware, increased RF digitization and the use of line replaceable modules.

Implications: Since the COTS market is extraordinarily dynamic, with new products being released every 18-24 months and new commercial "standards" constantly changing, obsolete processor and network parts will result in the "building codes" of the architecture changing over time. For example, we can no longer depend on building blocks being interconnected by MIL STD 1553 or some other standard network protocol, nor can we expect standard processors, such as MIL STD 1750 to be in existence in the far future. Commercial networks and processors having a 4-5 year parts availability will eventually become common place. For currently-fielded avionics, 1553 networks will likely be bridged over to new COTS networks and processors, with older military-based equipment being gradually removed with time.

In some ways, history is repeating itself in that we are returning to the 1960-70 era of proliferation of hardware and software designs. Some would argue that the main difference, that of using COTS instead of custom military designs, results in even more flux in that the COTS parts obsolescence problem and the rapid pace of market place changes further increases the integration, retrofit and and repair problems.

Two messages relating to COTS are clear however. First, the military has little choice in the matter because of our minute presence in the microcircuit market and our dwindling budgets (about 1.5% of global sales). Second, the technologies that are causing the "problem" will also bring the solution. That is to say, the use of COTS processors will allow the extensive use of automated design and simulation tools. Computer-based simulation tools will be used to capture the present state of the architecture and to analyze the impact of changes so that the proposed use of various COTS hardware and software can be quickly assessed before weapon system commitment. And possibly more important, automated computer-based software validation tools will be used to reduce costly flight testing. Attributes of architecture will be automatically encoded into VHDL designs for implementation.

Further, a greater reliance on programmable interfaces (vice custom ASICS) will be required to help accommodate COTS changes at the network level. Field programmable gate arrays (FPGAs) will be increasingly used to encode protocol and data security features. VHDL descriptions of network protocols will need to be available to quickly reprogram these FPGAs. It will be mandatory that operating system software and the various software interfaces that separate it from the hardware be developed in a highly modular fashion to mask network and processor changes from the application software to avoid costly re-validation. In addition, some architectural building blocks such as preprocessors which have previously been considered static over the life of the system will also need to be implemented in FPGAs. As a result of this new era of uncertainty, the avionic system architect will find himself increasingly relying on computer-based simulations, data

bases and VHDL routines to design and control the avionics system design.

The drive for low cost and the desire to support high speed data streams will also lead to more unified networks which have fewer stages of optical-electrical interfaces between the system network and the backplane. Not only will hardware cost and weight be reduced, but less-complex control software will be possible to permit system connectivity from sensor, processing, memory or display modules. Many of the concepts of integration, sharing, common modules and reconfiguration that have been successfully applied in the digital processing realm will be applied to RF systems in order to lower sensor cost while providing architectural versatility needed to exploit off-board information.

3) Technology Building Blocks: Future architectures will be shaped by significant strides being made in both COTS and military technologies. In general, COTS advances that will affect military avionics are being made in the digital processing and network areas in response to the vast personal computer market, with some COTS RF circuits from the telecommunications industry recently being available for use. Figure 1 shows the massive strides being made in COTS data and signal processors. Not only will military avionics use these products with proper packaging and cooling, but the extremely high speed processing required to accomplish future improvements in situation awareness will be feasible. Table 1 shows both the data rate and processor projections needed to support several situation awareness enhancements for the 2010 time frame era. (Ref 1). It is important to note that these are conservative forecasts since some forecasts indicate much higher data rates and processing speeds being required in the future.

Table 2 shows the characteristics of current digital networks available to the avionics architect. Note that these networks are generally too slow to meet the data rate projections in Table 1 without extensive numbers of parallel interconnects. Further detail regarding emerging photonic networks is shown in Table 3. Although photonic networks offer the future promise of achieving the needed speeds of about 2-3 gigabits/second, this table shows that much work still needs to be done, particularly in reducing the cost of photonic components. Under a Defense Advanced Research Projects Agency (DARPA) project beginning in early 1997, digital photonics building blocks in this speed regime will be developed for availability in 2000.

Figure 2 shows Harris Corporation's projections for COTS-based conventional and programmable gate arrays that will allow protocol and preprocessor changes to supportThe architecture updates. The upper line in the Figure shows the maximum advertised size of conventional (non-programmable) gate arrays, the next lower dotted line shows a more conservative projection for conventional gate arrays and the lowest dotted line shows a conservative projection of FPGA technology. The top, relatively flat curve shows an estimate of the gates needed to program a sophisticated COTS protocol such as Scalable Coherent Interface (SCI). Note that the Figure shows that we will soon have the capability needed to quickly adapt to new network protocols through VHDL designs. As a point of reference, the lower curves on Figure 2 show the number of conventional gates used on the high speed data bus (HSDB) and fiber optic transmitter receiver (FOTR) networks shown in Table 2.

The impact of COTS in the RF sensor arena has just begun as a result of the telecommunications industry which will impact military communications designs. In general, lowering the cost of RF sensors through technology will require military-custom analog and digital components. The most striking change in RF technology will be the increasing movement of A/D conversion towards the aperture because digital RF processing eliminates costly mixers, oscillators and amplifiers while providing improved performance. A/D converters that can provide eight bits of resolution at a 3 gigasample/second sampling rate have been built and several technology programs are underway to increase both the resolution and the sampling rate..

Implications: Future architectural building blocks will be much more compact, with several functions previously accomplished by several black boxes being done in a small box or module. As a result, dramatically increased signal processing and network data rates will result, along with the need for highly advanced packaging in the digital sensor area. Since these technologies allow improvements in situation awareness (e.g., longer detection ranges for RF sensors), weight and cost savings (e.g., elimination of expensive analog mixers, amplifies and filters) and will allow programmable adaptability, the author believes that they will be used extensively. *These technologies are re-opening the argument whether future systems will be distributed or integrated.* For example, if current network speed limitations could be removed by the use of multi-gigabit per second photonic networks, further integration of pre-processor, signal processor and data processor functions could be centrally integrated in a common processor rack with attendant weight savings and increased opportunities for sharing of processing assets. On the other hand, the increasing low cost and functionality of microcircuits (more gates on a chip) suggests that increased dedication of functions may be affordable in the future in order to exploit some of the advantages of federated architectures (e.g. less complex software, improved battle damage tolerance, tailored/higher performance designs, more easily-aligned vendor responsibilities and accountability, etc.).

The author believes both views have merit but that additional considerations will lead to the conclusion that a hybrid architecture will result. Since higher-level fusion, system health, system control, reconfiguration, display and stores and vehicle management interface *functions* must be performed, an integrated processing function will still be required. However, there is no reason to believe that this function must

be physically centralized, nor should sensor and processing functions necessarily will have to physically or functional separate in the future. The rationale to support these statements flow as a natural evolutionary step in the history of architectures. This history is described below.

2 ARCHITECTURE EVOLUTION

Avionic architectures have evolved from their predecessor as a result of network bottlenecks caused by an attempt to satisfy the need for improved situation awareness or performance. Figure 3 shows a simplified model of the process involved. Situation awareness improvements are enabled by the addition of improved sensors and displays and made possible by advanced digital processing capabilities. Eventually, a state is reached where the current physical, functional and logical configuration of the avionics (i.e., the architecture) cannot continue to support the steadily increasing flow of information between sensors, processors and displays. *A network bottlenect occurs.* If the data carrying capacity of the system interconnect structure can be cost effectively upgraded by the addition of additional or faster networks, the life of the architecture is extended. If however, a new functional and/or physical partitioning results that requires a fundamentally new network design to remove bottlenecks, a new architecture class evolves. It is interesting to look at how the characteristics that describe the architecture have evolved over time by looking at several trends reflected in several Figures. Figure 4 shows an exponential increase in data and signal processing capability that has mainly resulted from the addition of sensors which provided improved situation awareness. Figure 5 shows that a similar growth of network rates have increased over time for several military aircraft. Note the Pace Pace projection is derived from a composite estimate from several contractor sources and is typical of the data network requirements for a multi-role fighter in the 2005-2010 time frame. Figure 6 shows a comparative estimate of how the processing technology growth and advanced packaging capability from 1990 to the year 2000 should manifest itself at the modular avionics level. Note that a ten-fold decrease in module count is predicted for twice the processing capability. These figures illustrate the model shown in Figure 3, viz., the availability of advanced componentry will permit the drive for increased situation awareness to be satisfied, but at the expense of driving up network speeds to interconnect sensors, processors and displays. The question to be addressed now is whether the need for increased network speeds shown in Figure 5 can be met with existing architectures or whether a new one is required to avoid a bottleneck.

With the above trend data in mind, we are now in a better position to understand the motivation behind why architectural configurations have changed over time and, in turn, forecast the next logical evolutionary step (see Figure 7). The earliest architecture, that of "independent avionics" resulted in a single-function thread from the aperture to a dedicated display, with the aircrew performing the integration function. Point-to-point (i.e., hard-wired) electrical links interconnected sensors, controls and displays and processors, which were initially analog computers. Note that the functions performed by these single thread approaches required little processing sophistication and low data rates.

The versatility of the digital computer doomed this architecture because of the resulting network bottleneck that resulted from its use. Despite limited memory and slow speeds (by today's standards), the first models of digital computers could perform several different data processing functions on a time sharing (i.e., multiplexed) basis. As a result, the outputs of several low bandwidth sensors (e.g., inertial platforms, air data sensors) were hard-wired to the digital computer through an I/O box which performed the multiplexing function at its interface to the computer. Eventually, the number of wires became so excessive that a data transfer bottleneck occurred, with the I/O box being more complex and costly than the computer itself. The solution was to extend the multiplex boundary from the I/O box/computer interface to all the information sources and sinks on the network by multiplexing signals over one wire media. Computer speeds had become fast enough to *multiplex the data on a system network and still achieve "real time" processing capabilities.* Federated avionics (Figure 7) was ushered in by time-sharing data over the physical interconnect media. This architecture, using the MIL STD 1553 (STANAG 3838) multiplex protocol is typical of the vast percentage of military avionics flying today and has proven to be highly versatile and useful despite its 1 Megabit/second speed limitation.

Although this architecture has been labelled as federated, this descriptor only applies to the single processor control feature (the logical part of the logical, physical and functional triad that makes up the architecture). In reality, this so-called federated system is an integrated parallel processing system which has a bus-structured interconnect system that physically extends over the aircraft. With the passing of time, several parallel 1553 busses have been added as the need for integration has increased (see Figure 5), with each bus performing such functions as navigation/weapon delivery, electrical power control, flight control, stores management, etc. It is important to note the following attributes of this highly successful approach: 1) the network is a bus-structured design that is used to interconnect *data processors, very low bandwidth state vector sensors and control devices.* 2) dedicated, highly custom pre-processors and signal processors were housed within a dedicated box which outputed low bandwidth data onto the 1553 network.

Referring to Figure 7, an integrated digital system architecture is shown next in the chronology. This architecture is typical of the one developed by the US Air Force under the Pave Pillar Program and is the basis of the

approach used on the US Air Force's F-22 and US Army's RAH-66 helicopter. This approach is characterized by the following basic characteristics: 1) a small family of system-common data and signal processing line-replaceable modular assets are housed in physically-separated common racks (see Figure 8), 2) any digital data or signal processor asset can be accessed at the common-module level through an integrated set of system-wide networks. Because of constraints in technology or the types of data being transmitted over the network, a hierarchy of networks using both photonic (serial, several meters distance) and electrical (parallel, backplane) interconnects are currently used.

Using today's technologies, networks limitations require the mixed use of both electrical backplanes to interconnect assets within say, one meter and fiber-based networks a the system interconnect level. The following interconnects can be affected: high speed, serial, point to point digital sensor/display-based information can be routed to the common integrated processor (CIP) racks by a photonic network; serial inter-rack data is transmitted over a high speed data bus; parallel electrical data is transmitted over the electrical backplane of the CIPs through a data network switch (to handle streaming sensor and graphics data); a parallel interface (PI) bus in the backplane provides control and low bandwidth data transmission between modules. The speed of the point to point links is a function of the technology involved. Current light emitting diode technology will allow about 400 megabits per second to be transmitted, with laser-based transceivers being available in about 3 years which should permit around 2-3 Gigabits per second rates to be achieved. The high speed photonic data bus is specified to operate at 50 megabits per second. (Ref 2).

Understanding the motivation behind the shift from a federally controlled, bus-structured design to the integrated, partly bus-controlled, partly point-to-point approach provides much insight into the basic axiom about architecture evolution. *Architectures change to overcome network bottlenecks caused by a drive for increased situation awareness, cost and weight savings or a combination of these factors.*

The motivation to move signal processors inside the CIP was partly aimed at controlling the spiralling cost of sensor-dedicated signal processors by using a small family of common modules that are system-level assets. Signal processors, previously part of the sensor under the federated architecture, have now been physically removed to the CIP. Very high speed digital sensor data, once confined to a local backplane at the sensor, must now be sent over a system-wide network. Since the network rates of streaming data from the preprocessors are measured in the hundreds of megabits per second, it is obvious that MIL STD 1553 cannot handle the traffic and a bus implementation is totally inappropriate for the continuous, streaming data ; a bottleneck has occurred and the architecture must change. A point-to-point distribution approach between sensor, CIP and displays is currently being used because the desired switch network (for added system-level fault tolerance) cannot be built due to technology limitations. Another motivating reason for this architecture is that system weight (and hence cost) could be substantially reduced by having both data and signal processors share the same rack and backplanes. All these characteristics resulted in supporting the earlier mission needs cited in this paper: improved situation awareness (data can be fused more easily because it is accessable across a common backplane), reduced maintenance manpower, improved sortie generation and sustained operation from austere bases are simulateously achieved.

The question to be asked is whether this architecture will "hold up" over the next 10-20 years. Obviously, the impact of the various trends, discussed earlier in this paper, must be assessed to answer this question.

3. Architectural Enhancements for Digital Systems

In order to support the increased system interconnect speeds projected for the future (see Table 2 and Figure 3), either a few very high speed networks will be needed or more low-speed networks will need to be added or a return to the federated architecture is required in order to avoid the network bottleneck which will obviously occur in the future. The author believes that a return to the highly-federated architecture (where processing assets will communicate over short distances across an electrical backplane and be loosely controlled by a bus-structured network) is not likely because the need to fuse data before pre-processing and the desire to achieve fault tolerance through reconfiguration is not optimized using this approach. One the other hand, adding more low-speed photonic interconnects and continue to use a hierarchy of expensive and bulky optical-to-electrical, electrical-to-optical, serial-parallel and parallel-serial conversion circuitry having diverse network protocols is also not appealing. Figure 9 shows the preferred approach, a high speed unified network which has a universal protocol that will result in the seamless integration of processing, sensor, memory and display and control assets.

This approach allows the use of the most appropriate physical configuration for the particular application, using only one basic protocol and (if the technology will allow), using only one type of physical media to interconnect processing assets down to the module level. Given that a switched-network approach is preferable (over fixed point-point), the "ideal" network would allow the point-point access of any module to any source or sink of information on the aircraft through a high speed photonic network. Over the near term, such an approach is deemed unlikely due to the excessive cost of the number (in excess of ten) of cross-bar switches required for the interconnection fabric for highly complex designs. Also, the use of a point-point approach to affect low speed control

and address functions will increase the complexity of the switches and will increase the number of switch nodes. Because a bus-structure is more appropriate for these kinds of low speed functions, buses are likely to remain in use for the foreseeable future to complement the switched networks.

Figure 10 shows the author's predicted implementation for the next architectural evolutionary advancement for the digital portion of the avionics system. The Very High Speed Optical (VHSON) switched network allows sensors and displays to be interconnected to the modular processing assets at a *cluster* level. Clusters are an assemblage of common modules that perform some processing task such as radar signal processing. This system network is projected to operate at about 2-3 gigabits per second using graded index multi-mode fiber and a laser-based transceiver multichip module located at each source and sink on this network A protocol-consistent bus implementation (likely metal at first) would interconnect cluster modules through the backplane. The features of this architecture are not sufficiently different from the "integrated digital architecture" to put it in a different class, although significant network enhancements have been made. Because of the modular nature of the integrated digital architecture, higher network speeds can be obtained by replacing slower speed circuitry with laser-based technology when it becomes available and modification of the backplane and modules can also be done using a modular approach.

This next generation system is expected to further evolve further, as shown in Figure 11. This Figure shows one implementation of an advanced digital system, where a photonically switched network is used at the backplane. It is important to note however, that as system network speeds increase because of photonics technology, the avionics architect will have additional freedom to place computing assets at various locations on the aircraft with ever-decreasing performance and weight penalities, while still accomplishing the necessary fusion and fault tolerance functions. However, because the network will still be highly switched-based and the computing assets are not necessarily dedicated to sensors, any advanced evolutionary steps do not result in returning to a federated architecture. As the cost of photonic components continue to be reduced, a photonic backplane implementation is expected to appear, possibly for aircraft entering service as early as 2010.

4. Architectural Enhancements for RF Sensor Systems

Although the above-described evolution in digital systems is not expected to result in a new architecture, the application of some of the same design philosophies, processing and network technologies, along with advances in analog RF circuits and A/D converter technology are expected to cause a major shift in the way radio frequency systems will be built in the future. In the author's view, the resulting integrated sensor system concept, combined with the advances described above, will permit such advanced integration capabilities that a new, "fourth generation" architecture will be introduced for application in the 2010 time frame.

Since over half of RF costs are due to the "support electronics" between the apertures and the signal processing assets, new technology building blocks will be targeting to drive these costs down. Strides being made in advanced GaAs analog circuitry will allow a small family of modular building blocks to be built which will perform frequency conversion, switching, receiving, signal generation and transmitter functions across radar, EW and CNI functions. The same dramatic cost, weight, maintenance and system availability benefits resulting from applying VLSI circuitry to the digital domain (which made the integrated digital architecture possible) will enable a new architecture to be developed for future sensor systems. A Wright Laboratory program called Integrated Sensor System (ISS) is currently underway to validate the practicality of this concept before the turn of the century. racks. About 20 module types are needed for a full system implementation. Although not shown in Figure 12, a digital photonic network interconnects each analog module to permit "microsecond-level" control and instantiation of internal switch settings, analog filter settings, etc. Top level resource management software is resident in core processing, which together with signal processors, are located in a CIP. The CIP and the ISS system are connected by a photonic, switched network. Referring to Figure 12, A/D converters are placed at the output of the receiver modules. High speed digital signals (ranging from a few hundred megabits per second to about 10 Gigabits per second) are routed through a switched network to interconnect receiver modules or pre-processors Figure 12 provides a simplified block diagram that shows the modular nature of the ISS approach. Although space does not permit a full description of this sensor architecture, the reader may wish to consult Ref. 3 for an explanation of its operation.

Note the close similarity of the architectural approach shown in Figure 12 to the one shown in Figure 10.

The following observations can now be made about the features of this fourth generation architecture for RF and digital processing functions: 1) the same modular design approach will be used for both functions, 2) the same types of digital switches for CIP and ISS architectures are needed for both designs and can be made to be identical, 3) a digital photonic network is needed to interconnect modules whether they are part of the ISS complex or part of the CIP in the future and they can be made to be identical, 4) with the increase of network speeds in the future, the placement of signal pre-processors in the ISS system or in the CIP becomes the choice of the designer, 5) because photonics will allow the co-habitation of digital signals and sensitive RF signals in a common backplane without interference, advanced modular avionics racks can support electrical RF and digital modules.

The fundamental conclusion to be drawn from these observations is that a new fourth generation architecture will

eventually evolve such that the avionics architect, for the first time in the history of avionics, *will have the design freedom to physically place analog, pre-processor, signal processor and data processor modular assets at any location on the aircraft depending on the availability of space and the need to fuse information.* The primary enabling technology which has allowed this capability is the advancement in photonic networks where system network speeds are on the same scale as backplane speeds. Figure 13 shows the implementation of this architecture. The reader should not assume that any of the modules shown are necessarily located close together or far apart. Network bottlenecks are removed, either by the use of high speed photonic networks at the system interconnect level or by the placement of modules close together across a photonic backplane. The author estimates that this kind of architecture could appear as early as 2010.

5. Future Evolutionary Enhancements

Figure 13 also shows the use of some new technologies which are expected to continue the evolution of this architecture. For example, the cost, performance and weight advantages resulting in dramatic increases in the speed and performance of A/D converters will allow the use of digital CNI and the digital boundary of the intermediate frequencies for both ESM and radar receivers will move one to two stages closer to the aperture. Digital data rates approaching ten gigabits/second will be needed to be switched between receiver and pre-processors, requiring the use of single mode fiber optics. Further, coax cable will increasingly be replaced by analog single mode fiber for RF and for local oscillator signal distribution. Further, strides made in optical heterodyning will allow the replacement of costly and bulky electrical frequency conversion hardware with highly compact optical components.

6. Conclusions

The history of avionics architectures is strongly controlled by a process that is driven by the desire to improve weapon system lethality and survivability through situation awareness enhancements. The process is highly evolutionary, with new sensors, processors and interconnecting networks being incrementally added until fundamental network bottlenecks forces the architecture to change to another plateau, where the process continues.

The current integrated digital architecture has only recently been introduced and has many years of growth potential remaining, although network speed improvements will be necessary to support increased processor speed requirements. However, because this architecture was designed with ease of retrofit in mind, these changes can be made relatively easy by the use of high speed laser-based transceivers and optically switched network modules in the CIP.

The most dramatic changes in architecture will occur in the area of RF support electronics, where many of the same features of modularity and resource sharing being currently used in the CIP will be adopted for RF systems. Because of advanced RF circuits, A/D convertors, digital processing and networks, the RF system architecture will become very similar to the advanced CIP architecture. The merger of these two architectures and the projected improvements in network speeds will eventually allow the emergence of the fourth generation architecture in the 2010 time frame.

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1. Morgan, DR & Lachenmaier R, et al, "Joint Advanced Strike Technology Program Avionics Architecture Definition", 5 Aug, 1994, available on request to ANSER/JSF at U. S. A phone number 703-416-3113.

2. Fraker, MJ and Blake, CL, " The F-22 Advanced Tactical Fighter and the Joint Integrated Avionics Working Group", 1992 ERA Avionics Conference Proceedings, ERA Report 92-0809, London, UK.

3. Morgan, DR & Mathews, K, "Integrated Radio Frequency Sensor System Architecture", AGARD Conference Proceedings 546 (AGARD-CP-546). "Challenge of Future EW System Design", May, 1994, held in Ankara, Turkey, 18-21 Oct, 1993.

TABLE 1
Data Rate and Throughput Projections (Circa 2010)

Application	Data Rate Per Channel MBITS/SEC	Throughput (Include Processing Preprocessing) (GOPS)
IRST	120-180	6-10
ATR	----	2-5
FLIR	120-160	3-10
SAR/MTI	800+	50+
EO	300-500	15-20
EW	1700-3500	5-11
Sensor Fusion		400 MIPS

TABLE 2

DIGITAL AVIONICS NETWORKS

NETWORK/NAME STANDARD	MAX SPEED MBITS/SEC	FUNCTIONAL USE	AIRCRAFT USE	MEDIA	PROTOCOL
MIL STD 1553B/ STANAG 3838	1	SYSTEM BUS	MILITARY AIRCRAFT	TSP*	COMMAND/ RESPONSE BUS
MIL STD 1773A	1 OR 20	SYSTEM BUS	TBD	FIBER	COMMAND/ RESPONSE BUS
ARINC 629	2	SYSTEM BUS	COMMERCIAL AIRCRAFT	TSP	COMMAND/ RESPONSE BUS
ARINC 636 (FDDI)*	100	SYSTEM BUS	BOEING 777	FIBER	COMMAND/ RESPONSE BUS
STANAG 3910	1 AND 20	SYSTEM BUS	RAFALE	COAX	TOKEN PASSING BUS
AS4074 (HSDB)	50	SYSTEM BUS	F-22, RAH-66	FIBER	TOKEN PASSING BUS
FOTR	400	HIGH SPEED STREAMING SENSOR & VIDEO DATA	F-22,RAH-66	FIBER	PT-PT-SERIAL
PI BUS (AS 4710)	400	BACKPLANE BUS	F-22	COPPER TRACES	COMMAND/ RESPONSE BUS (PARALLEL)
DATA FLOW NETWORK (AS 4709)	800	BACKPLANE SWITCH	F-22	COPPER TRACES	PT-PT-SWITCH (PARALLEL)

TSP ~ TWISTED SHIELDED PAIR

ARINC ~ AIRBORNE RADIO INCORPORATED

FDDI ~ FIBER DISTRIBUTED DATA INTERFACE

HSDB ~ HIGH SPEED DATA BUS

FOTR ~ FIBER OPTIC TRANSMIT/RECEIVER

TABLE 3
Available Avionic Networks (Circa 1994)

Parameter \ Bus Protocol	ARINC 429	1773	Dual Speed 1773A	STANAG 3910	ARINC 629	ARINC 636 (FDDI)
Availability	now	now	now	now	now	now
Optical Receiver cost	$175	$1000 (XCVR)	$500	$1500	$1000	$200
Optical Transmitter cost	$150		$244	$1200	$800	$150
Protocol Device cost	$112	$650	$800	$400	$200	$300
Temperature range	MIL	MIL	MIL	MIL	MIL	Designed to 883, no testing
Data rate	100KB	1 mbps	20 mbps	1 and 20 mbps	2 mbps	100 mbps
F.O. Cable Interface	100/140	100/140	100/140	100/140	100/140	100/140
U.S. Current and Future Standards Compatability	yes	yes	yes	no	yes	yes
Manufacturer	Honeywell Motorola Holt	Litton Polyscientific, SCI	Litton Polyscientific, SCI (4th Q)	SEL, Alcatel	Litton Polyscientific, Boeing	
FC suitability	yes	yes	yes	yes	yes	no

Source: Flash Program, McDonnell - Douglas Aircraft

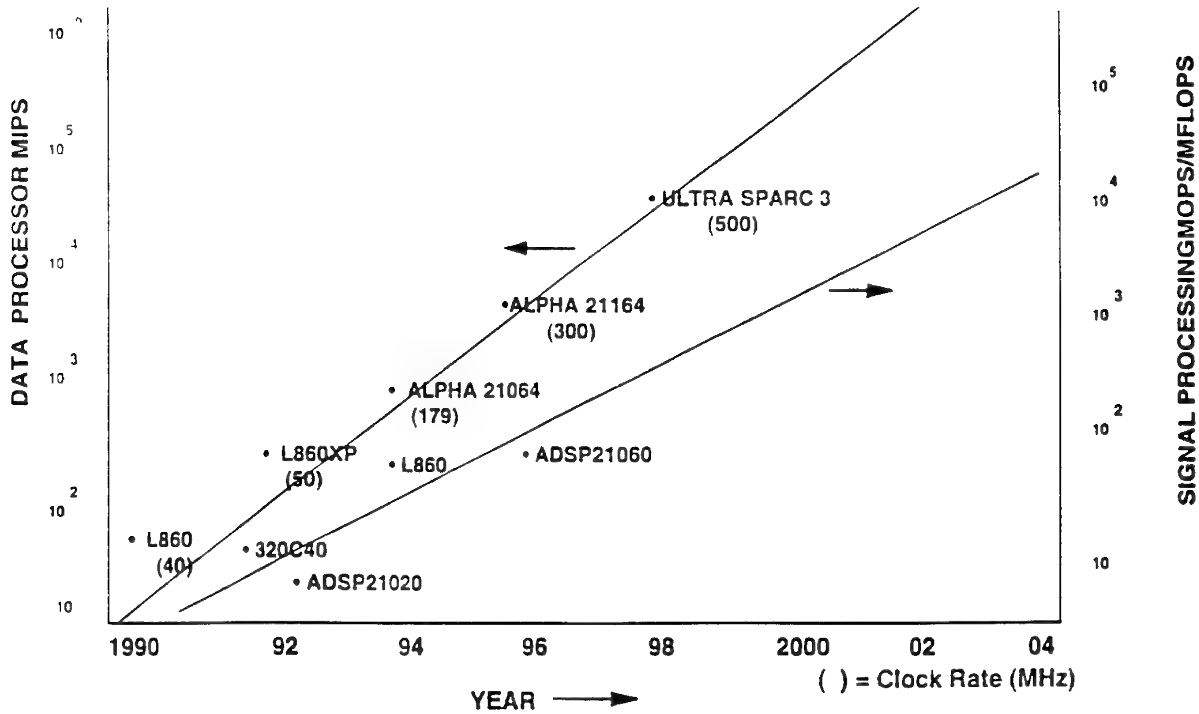

Figure 1

Commercial-Off-The-Shelf Data & Signal Processor Forecast

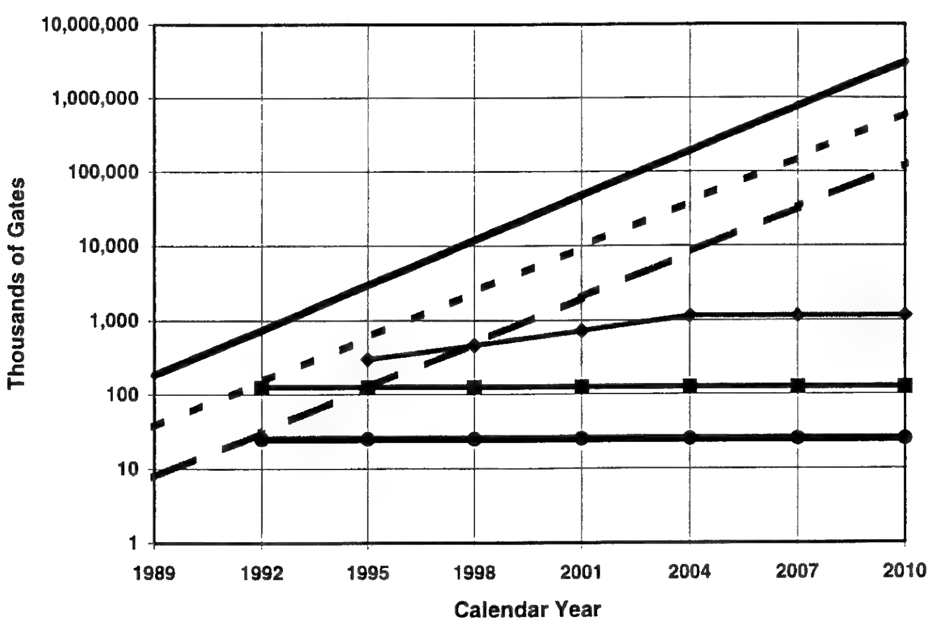

Figure 2

Projected Sizes Of Gate Arrays

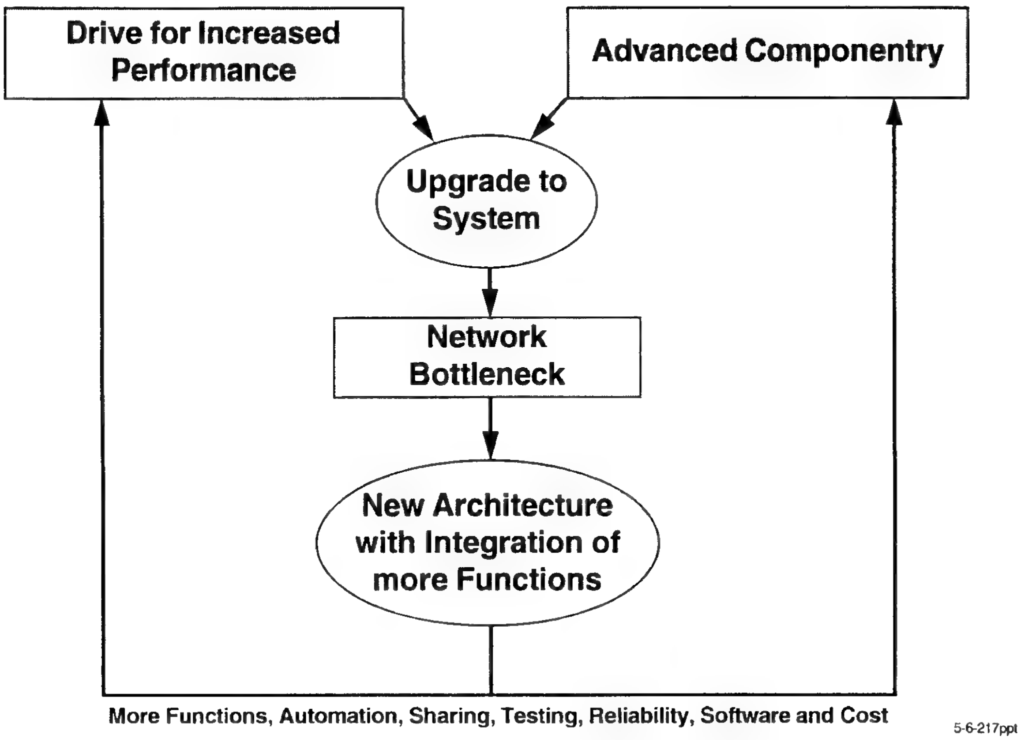

Figure 3
Avionics Architecture Evolution

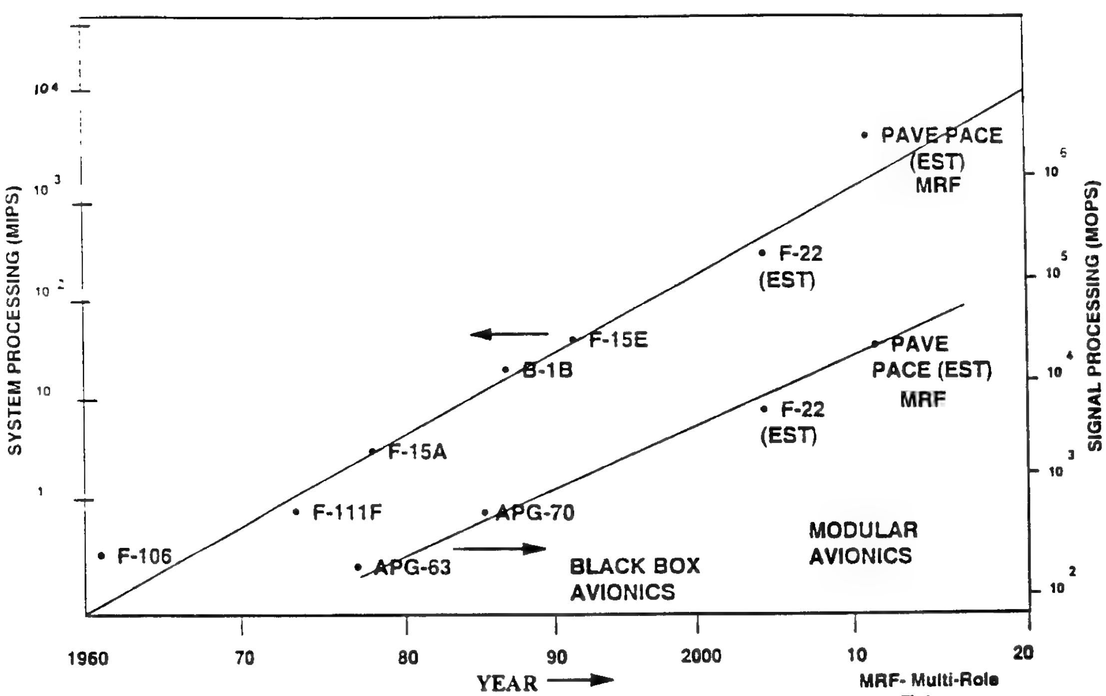

Figure 4
Evolution Of Digital Processing

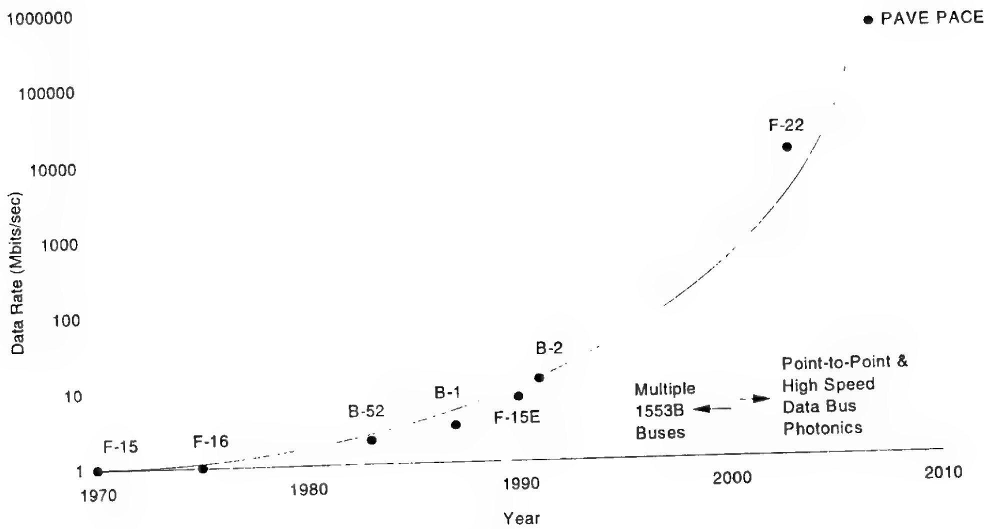

Figure 5
Growth of System-Level Network Speed

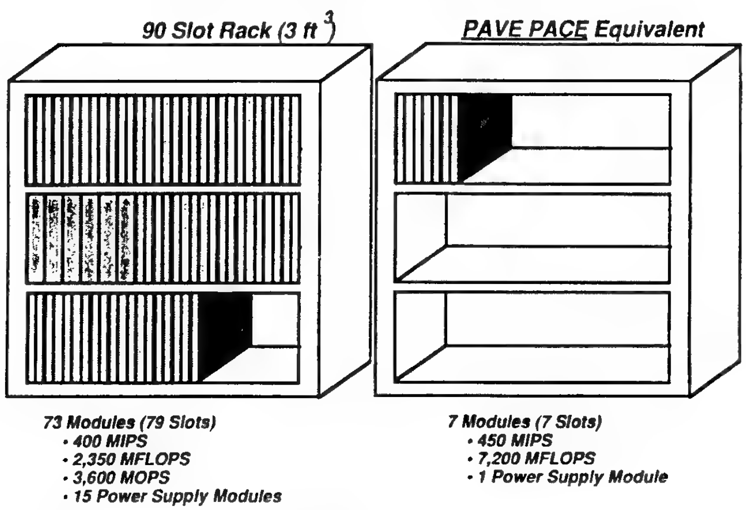

Figure 6
Processor Technology Impact

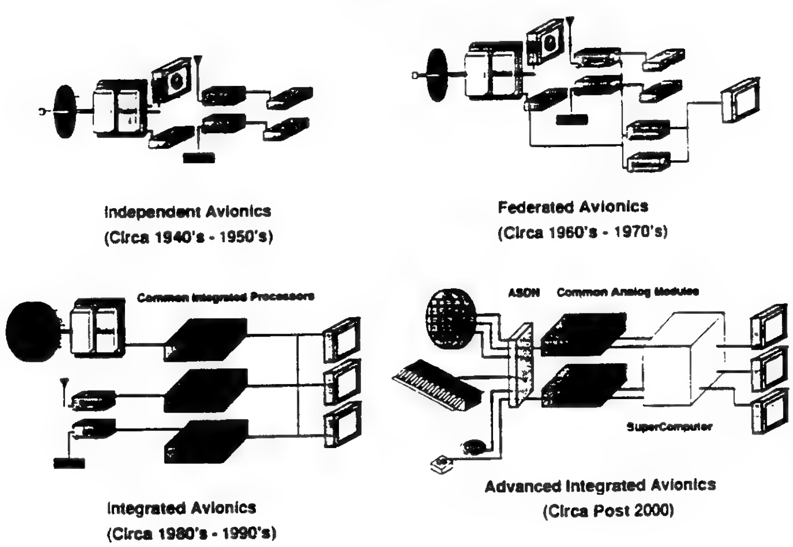

Figure 7
Architecture Evolution Configurations

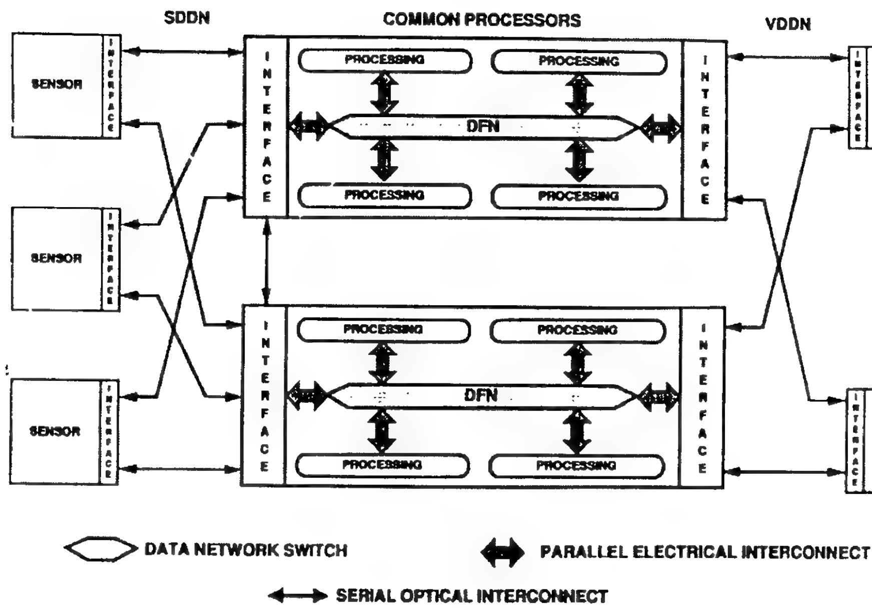

Figure 8
Integrated Digital Avionics-Third Generation Architecture

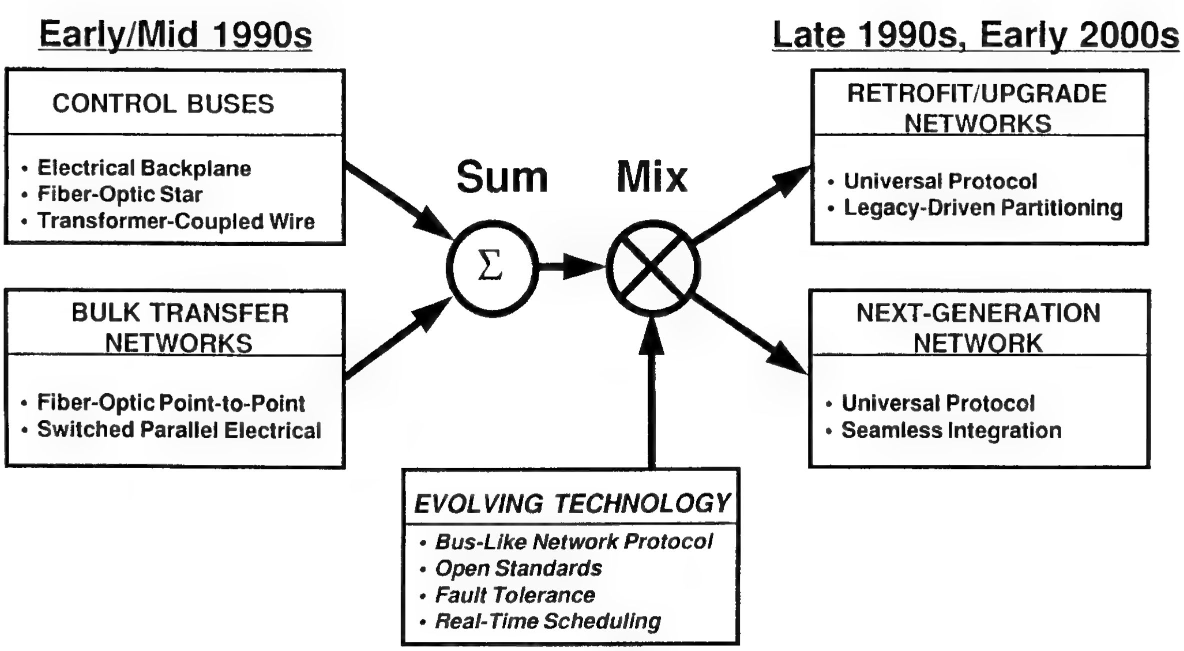

Figure 9
Network Evolution

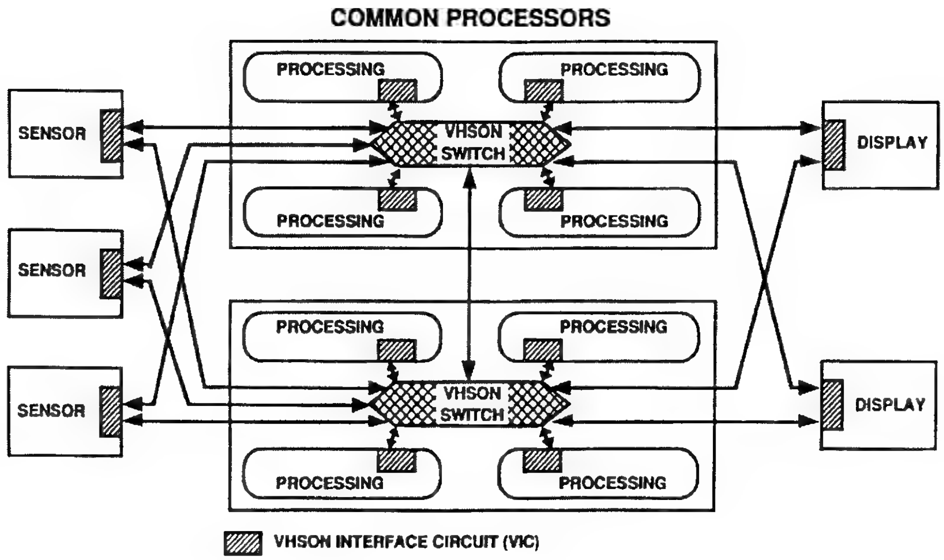

Figure 10
Advanced Integrated Digital Avionics

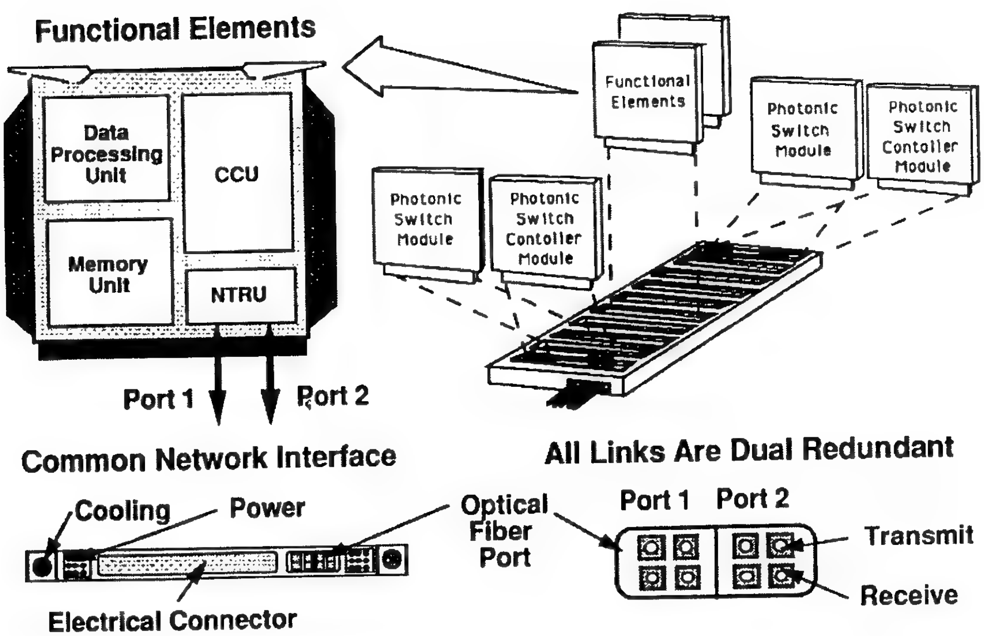

Figure 11
Functional Elements of a Photonic Backplane System

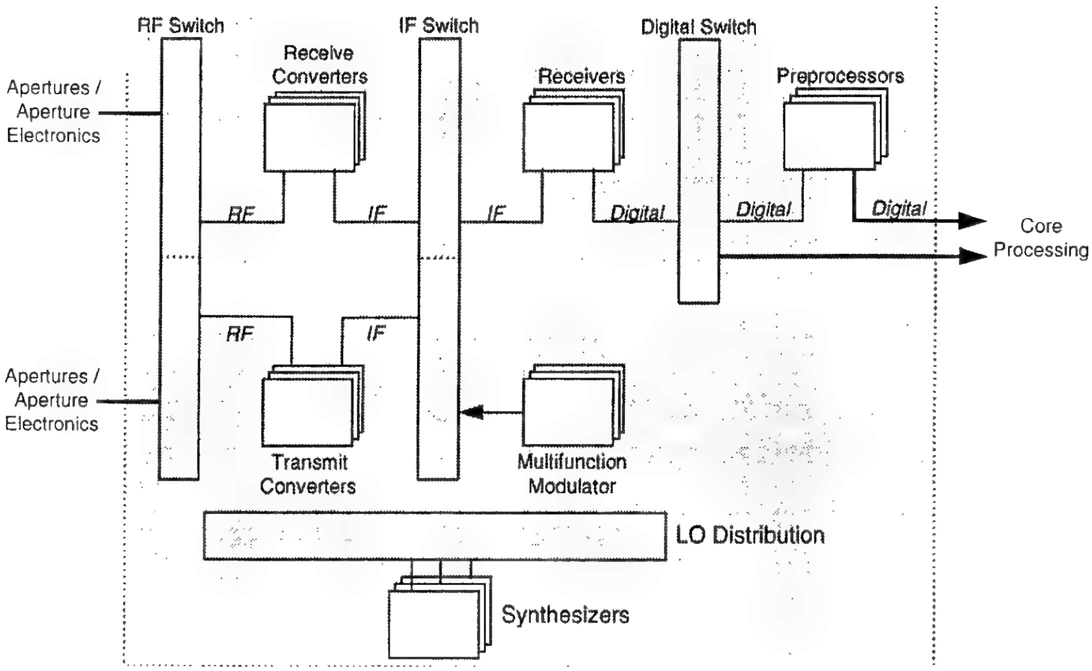

Figure 12

Simplified Diagram of Integrated RF Sensor System

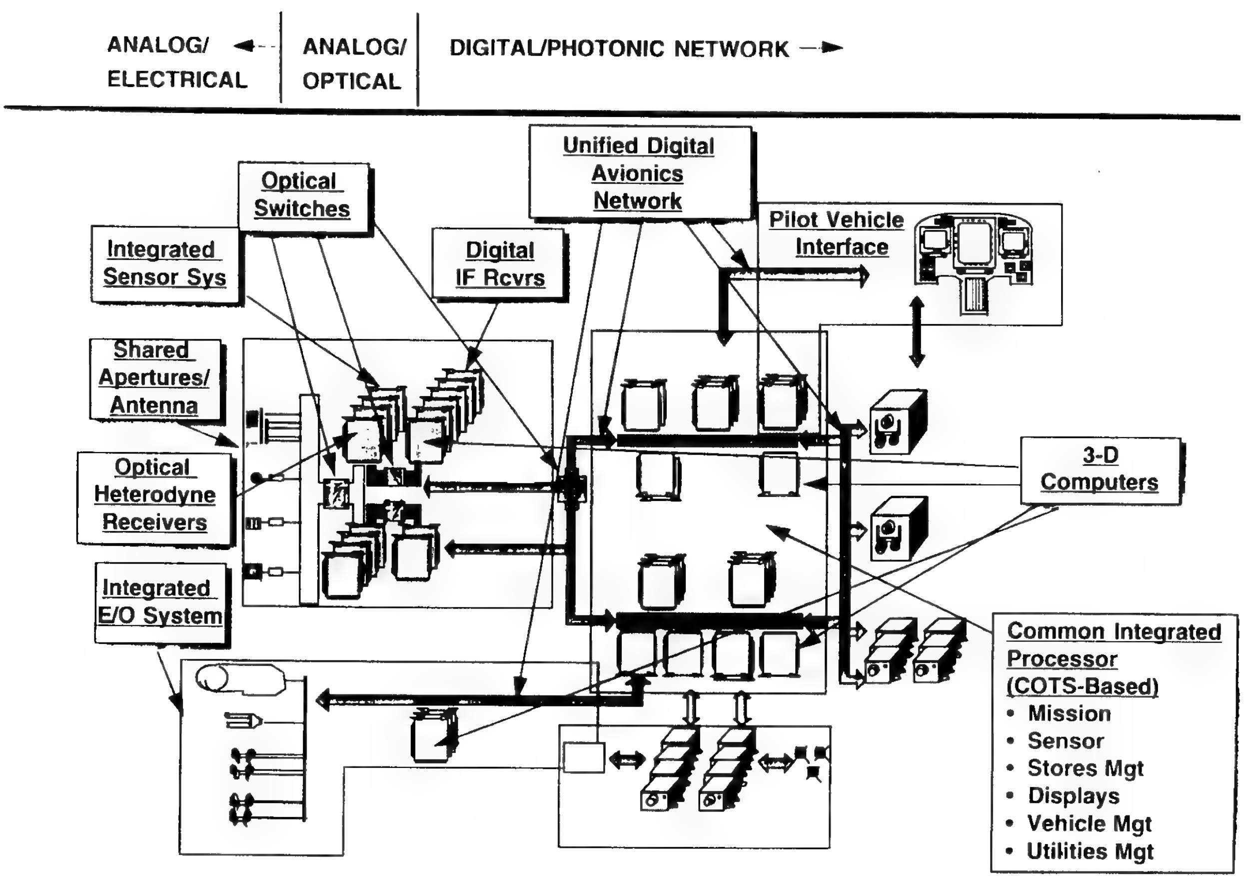

Figure 13
Future Avionics Architecture

Technology Transparency in Future Modular Avionic Systems

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1 SUMMARY
Affordability is a key driver for future weapon systems, and it is generally accepted that integrated modular avionics (IMA) can make a major contribution to the reduction of acquisition and support costs. However, the technologies upon which IMA depends are evolving rapidly, and there is a danger that emerging IMA standards and systems under development will become obsolete over timescales which are short compared to military programme lifecycles.

This paper suggests that steps can be taken to mitigate the impact of obsolescence on complex avionic systems by ensuring that *technology transparency* is established as a key architecture characteristic, and is tackled from the outset in standardization activities and in system design.

The importance of technology transparency is a consequence of the rate of technology development in relation to the long system lifecycle for military projects, and the need for interchangeability and backwards compatibility of new building blocks in "old" systems in order to reduce life cycle costs (LCC). Examples of how technology transparency can be achieved are given for the hardware, software and data networks domains.

Key areas for long term "open system" interface standards which support technology transparency are identified, based on information previously released from the Allied Standard Avionics Architecture Council (ASAAC) standardization programme (Reference 1).

The implications of system level issues (safety, security, qualification, etc.) and the drive to exploit Commercial Off The Shelf (COTS) technology are explored, and the need to consider technology transparency for system design tools is established.

The main conclusion is that, whilst many regard technology transparency as the "Holy Grail" of IMA, practical solutions are possible in a number of areas and must be pursued vigorously through programmes such as ASAAC if LCC benefits are to be maximized.

2 WHAT IS TECHNOLOGY TRANSPARENCY?
Technology transparency is a system property which summarizes the ability of a particular system to accommodate two aspects of growth: system growth and technology growth.

System growth is the incorporation of new or enhanced capabilities in a system at various points in its life, typically achieved in current military aircraft through a Mid-Life Update (MLU). The large scale MLU approach has now fallen out of favour, with customers preferring smaller and more frequent incremental updates which spread the cost more evenly. The flexibility offered by Integrated Modular Avionics (IMA) allows these incremental updates to be catered for in the initial system design, giving rise to the term Pre-Planned Product Improvements (P^3I).

Technology growth is the incorporation of the latest technology with minimal disturbance of the system in order to support system growth, or to minimize support costs which would otherwise be incurred in the maintenance of obsolete technology.

A *technology transparent* system should be able to incorporate new requirements and new technology with minimal impact on Life Cycle Costs (LCC).

3 IMPORTANCE OF TECHNOLOGY TRANSPARENCY
Technology transparency is important because it will be a major factor in determining the LCC of future avionic systems. Areas where technology transparency can help to reduce LCC include:

- Design changes/upgrades
- Backwards compatibility
- Interchangeability
- Exploitation of commercial technology
- Obsolescence

3.1 Design Changes/Upgrades
When upgrading a system to incorporate new requirements it is generally necessary to add supplementary hardware/software to the existing system. Future IMA systems must provide a high level of flexibility in the selection of the most appropriate current technology in order to satisfy the new performance requirements, whilst minimizing LCC. The technology used for the original system design will not necessarily be sufficient in terms of performance.

Design changes in one part of a system tend to have an impact on other parts of the system, particularly as system complexity increases. The cost of dealing with these "knock-on" effects can be considerable, especially in terms of system requalification. Technology transparency can help to limit the propagation of design changes throughout a system.

3.2 Backwards Compatibility
Backwards compatibility is the ability to use new system elements in an old system to replace older elements of lower performance, with no adverse effect on system operation. The system need not *necessarily* exploit the improved performance which they make available, the intention may be to obtain logistics benefits by supporting a range of aircraft types with a small set of common items. Since all the old elements might not be replaced by new ones at one point in time, future IMA systems must be able to automatically adapt to the presence of items of different generations in order to partition the applications on the overall new system in the most appropriate way. Lack of backwards compatibility would mean extensive redesign of existing systems to incorporate new elements, or the maintenance of large stocks of dedicated spares. Again, one of the goals of technology transparency is to minimize the cost of redesign/requalification.

The rate of technology development produces many generations of new technology over the lifetime of a military aircraft, which could easily be 40 years from initial design to disposal. For example, the performance of data processors is doubling every 18 months at the moment. In view of the pressure to reduce military budgets, exploitation of the cheapest current technology is becoming vital to the maintenance of capabilities to design, produce and support new weapon systems. Without technology transparency it would be necessary to take into account, starting with the initial design, all future growth modifications of the system and make the necessary provisions (mass, volume, cooling, power) with an assumption of no technology upgrade possibility without almost complete redesign of the system.

Backwards compatibility can also be regarded as an extension in time of another important goal of (IMA) , interchangeability.

Paper presented at the AGARD MSP Symposium on "Advanced Architectures for Aerospace Mission Systems", held in Istanbul, Turkey, 14-17 October 1996, and published in CP-581.

3.3 Interchangeability

Interchangeability is the ability of modules of the same basic type and conforming to a common standard in terms of interfaces, behaviour and minimum performance to be exchanged with each other with no adverse impact on the target system(s). Future IMA systems must be able to accept modules of the same type produced by different manufacturers to a common standard but using different implementation technologies. As for backwards compatibility, one of the main drivers for this is the need to reduce the logistics burden. Further cost benefits may be realized due to decreased dependence on single-source suppliers.

3.4 Exploitation of Commercial Technology

Most of the necessary technologies are driven by non avionic industries (and more particularly by computing and communication industries). The consequence is that those industries can produce much cheaper and more capable technology at any given time. They also drive the high rate of technology change. The avionics industry can no longer afford its own specific technologies and needs to exploit those driven by other industries.

3.5 Obsolescence

As the electronics industry is market driven, the technologies are very quickly obsolete and not supported for a very long time by the electronic components manufacturers: around 3 years for data processors, interface drivers or memory. The cost of supporting obsolete technology is very high, with semiconductor manufacturers becoming increasingly unwilling to cater for the relatively small military market. The pace of obsolescence is still slower for other technologies but will probably increase during the next decade, mainly in the network domain with the arrival of high performance protocols and large bandwidth physical support such as fibre optics.

Design and development tools used to be specific, but more and more generic tools usable for avionics are appearing on the market. This trend will increase as the technologies used by the avionics industry and the commercial market converge. Tools which are designed with current technologies in mind will become obsolete at a rate similar to the electronic component obsolescence rate.

Software technology in the operating system and language domains is still evolving at a lower speed than hardware because of the immense investment in time and effort needed to produce each standard. However, it is important to pay close attention to the development of software technology because software costs have a large impact on the affordability of complex systems.

At the module level, packaging and assembly materials and processes are also developing quickly, leading to shorter lifetimes for very specialised and expensive manufacturing and repair equipment. The primary goal of technology transparency is then to ensure that when new technology is incorporated into a product it remains totally backwards compatible with existing products of the same type already in the field. This approach will greatly reduce the logistics burden for the users, as well as allowing the most cost-effective technology to be adopted on a rolling basis.

When a technology is changed inside a system, the system requires requalification. In a rapidly changing commercial environment, the degree of requalification necessary must be minimized in order to reduce costs. Technology transparency can be exploited to restrict the scope of requalification when new technology is introduced.

4 ACHIEVING TECHNOLOGY TRANSPARENCY

The examples given below are intended to demonstrate that technology transparency can be incorporated into IMA concepts. Three areas of technology are addressed: electrical power supplies, software and optical data transmission.

4.1 Technology Transparency - Power Supplies

A good example of how technology transparency can be achieved in IMA is provided by the distribution of electrical power to line replaceable modules (LRMs) in a rack via a backplane. A common method is to use a number of power conversion modules (PCMs) to convert the platform electrical supply voltage to logic levels (sometimes in two stages), which are then routed along the backplane as dedicated rails and picked up by the appropriate LRMs (Figure 1). This may be an efficient approach at a particular point in time, but from the point of view of technology transparency it has a number of serious weaknesses.

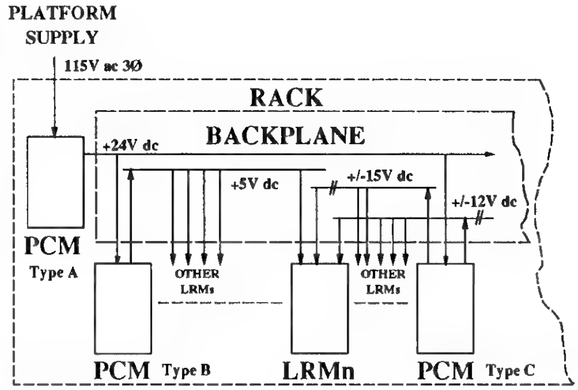

Figure 1: Conventional Power Distribution

Firstly, a number of different voltages must be generated to cater for the different technologies used by the full set of LRMs, e.g. +5V, ±15V, ±12V, -2V, -5.2V, etc. This increases the complexity of the electrical backplane, giving rise to many dedicated individual power and return paths, each of which must be assigned to a separate pin in the common LRM connector. A number of different PCMs may be required to cover the full range of voltages.

Secondly, the technology development trend in semiconductor logic is for lower voltages in order to reduce electrical power requirements and heat dissipation, with +3.3V replacing +5V at the moment and progressively lower voltages planned by manufacturers. PCMs dedicated to particular logic levels can therefore become obsolete rapidly as LRMs incorporating the latest technology are brought into the system. Backwards compatibility of new LRMs in old systems may therefore be difficult to achieve without expensive large scale refits.

Thirdly, electronic packaging densities are increasing, leading to higher LRM electrical power requirements and heat dissipations (even though the trend for many individual devices is in the opposite direction). Some sources predict liquid flow through (LFT) cooled modules with dissipations in excess of 200W, which would result in a backplane/pin current for a single LRM of more than 60A! Even if LRM electrical power requirements can be constrained to levels which are compatible with conduction cooling, the conventional approach to power distribution leads to unacceptably high backplane currents and voltage drops.

A technology transparent solution to these problems is to distribute a single dc voltage on the backplane and provide dedicated dc to dc converters at the point of use on each LRM (Figure 2). The backplane voltage must be high enough to keep backplane currents and voltage drops within acceptable limits for the anticipated range of LRM power consumptions. The two leading contenders at the moment are +48V and +270V. A useful analogy in the commercial world is to regard the desktop PC as being equivalent to an LRM in an IMA system. The PC electrical power supply interface has very good technology transparency, catering for two external supply voltage ranges (100 to 125V ac and 200 to 240V ac) via a single standard three pin connector and a voltage range selector switch.

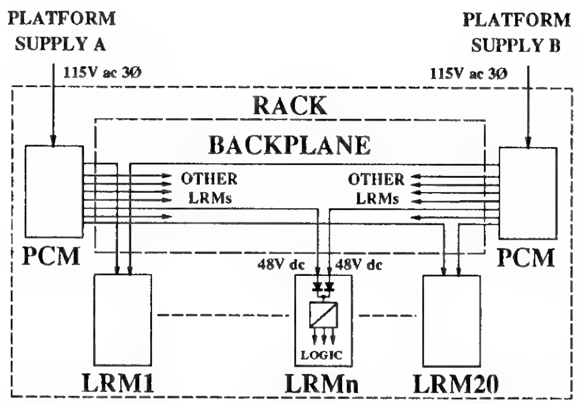

Figure 2: Technology Transparent Power Distribution

4.2 Technology Transparency - Software

An example of how the achievement of technology transparency can be more challenging is provided in the software architecture (Figure 3). The software operating system is a vital component of IMA which plays a central role, not just in controlling the whole system, but also in achieving independence of the application software from the underlying hardware. Hardware/software independence is a key IMA property which helps to deliver multi-vendor LRM interchangeability in the short term and technology transparency in the longer term. A well defined and stable Application to Operating System (APOS) interface is part of the answer, but the need to avoid application software and operating system recompilation when the target hardware is changed means that technology transparency must also be taken into account in the definition of the lower level Module to Operating System (MOS) interface and the Module Support Layer (MSL).

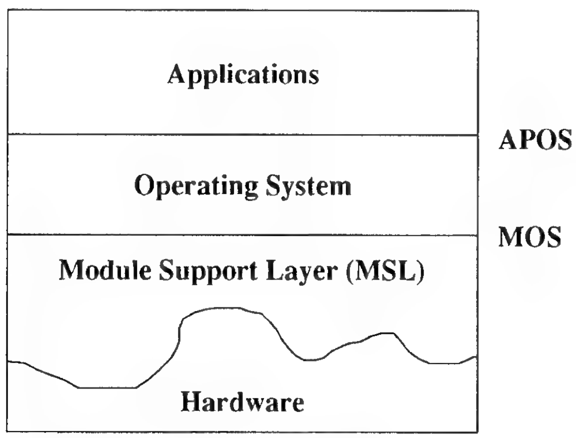

Figure 3: Software Architecture Model

The MOS interface can be described in terms of two components, functional and physical. Like the APOS, the MOS functional definition consists of a set of services and is relatively straightforward. The physical component describes the processing hardware configuration details (word length, instruction set, registers, etc.), which will vary from supplier to supplier and will change as technology advances. A number of approaches to interchangeability/technology transparency are possible at this level (Reference 2), with the Virtual Binary Interface (VBI) and the Virtual Object Interface (VOI) being the leading candidates.

Both VBI and VOI overcome the problems posed by differing implementation configurations and capabilities for LRMs of the same type by imposing a single standard physical description of the hardware which defines a "virtual machine". The application software and the operating system are compiled to execute on this virtual machine, and the MSL supplied by the LRM manufacturer must then handle translations between the virtual machine and the actual native hardware. The Virtual Binary Interface carries out this translation at the binary level as each instruction executes, giving binary code portability. The Virtual Object Interface incorporates an "install" routine in the MSL which is invoked when the software is first loaded, carrying out the translation just once prior to execution. VOI therefore allows object code reuse.

Although VBI and VOI appear to have the potential to deliver interchangeability and technology transparency, more work needs to be done to establish whether the performance penalties of these techniques will be acceptable in a practical IMA system. This is a challenging topic, but it might not be necessary to adopt VBI/VOI for the first generation of IMA technology as there may only be one supplier per LRM type in a particular project. An appropriate technique could be used as more capable technology became available and LRM supplier diversity increased. However, it is encouraging to note that more and more commercial processors are able to emulate other manufacturers' devices using a variety of techniques.

4.3 Technology Transparency - Optical Network

The final example looks at the data transmission network, and illustrates how difficult it can be to guarantee technology transparency.

There are two main data network interface areas. The higher level Network Independent Interface (NII) allows the software (applications and operating system) to make use of communication services without knowledge of the network protocols and technologies. The NII is effectively part of the lower level operating system interface, the MOS, and should not be a problem from the point of view of technology transparency.

The lower level Module Physical Interface (MPI) has electrical, optical, mechanical and cooling domains, all of which are exposed at the physical boundary of the LRM. Technology transparent interfaces for these domains must therefore be carefully defined so that LRM interchangeability, interoperability and backwards compatibility are preserved whenever the underlying technology changes. The optical interface domain poses the biggest problems for technology transparency in the MPI.

There seems to be a general consensus that future IMA data networks will be based on serial optical fibre paths with individual channel capacities measured in gigabits per second. As data and signal processing capabilities are likely to continue to grow rapidly, the challenge for the data network physical interface is to provide sufficient bandwidth (perhaps in the form of multiple ports per LRM) to fully exploit LRM processing capabilities. The history of PC development shows that a particular data communication technology can rapidly become a bottleneck in the system, drastically limiting overall performance.

Optical data transmission offers enormous potential for increasing bandwidth as time goes on, but the dilemma at the moment is that there are numerous permutations of optical technology options which *might* be technology transparent. At this early stage of development there is insufficient information on future trends and risks to make confident decisions on which options to design into the first implementation. Single mode fibre with laser transmitters appears to be the most technology transparent combination but is perceived to be the highest risk, especially with regard to connector contamination and vibration performance. Lower risk options such as graded index fibre with light emitting diode (LED) sources have more limited growth potential but could probably satisfy the performance needs of first generation IMA systems. The decision is further complicated by the need to minimize costs, which encourages the use of commercially available technologies and devices in preference to unique solutions.

The problems in setting technology transparent standards for the optical interface to LRMs are therefore:

(a) Future high performance LRMs may be forced to adopt new technology which is not backwards compatible with first generation low risk technology.

(b) The technology selected today may not be cost effective in the future if it does not have long term commercial support.

(c) The most technology transparent options tend to carry the highest risk in the short term.

(d) There is no *guarantee* that optical communication will be adopted - research into high frequency electrical alternatives is continuing.

Fortunately, a considerable amount of R&D effort is being put into this topic!

5 STANDARDS

The previous examples show that the key to achieving interchangeability and technology transparency is the creation of stable interfaces, which implies a need for interface standards. Hardware and software interfaces must be very well defined, taking into account the likely growth in the requirements of users and technology development so as to avoid performance bottlenecks and technological dead ends. Module behaviour behind the interfaces must also be explicitly defined, but in a way which is independent of the implementation technology. Technology dependent factors such as performance need to be separated out from interface and behavioural descriptions, for example as "slash sheet" supplements to standards. The definition of technology transparent standards for IMA is challenging, but is feasible if the emphasis is focused on interface standards rather than product standards.

5.1 Interface Standards

The key interfaces which were selected for standardization in Phase I of the ASAAC programme (Reference 1) and used for the examples in section 4 are summarized below:

	SOFTWARE
APOS	Application to Operating System - the higher level operating system interface to the application software
MOS	Module to Operating System - the lower level operating system interface to the hardware/firmware
	DATA NETWORK
NII	Network Independent Interface - the higher level firmware to operating system interface (at or below the level of the MOS)
	PHYSICAL
MPI	Module Physical Interface - split into:
	Electrical Optical Mechanical Cooling

5.2 Open Standards

IMA standards need to give the system integrator and the system user a degree of supplier independence by allowing alternative sources for a particular building block, hence the importance of interchangeability and technology transparency. This will permit more flexible purchasing decisions to be made on the basis of supplier performance, cost and schedule factors. Although some manufacturers may feel uncomfortable about potentially having to compete for ongoing business in a particular project, the fact that supplier independence encourages supplier competition should be seen as a way of preventing a single manufacturer from totally dominating the market. From the point of view of the supplier, standards must bed designed so as to provide opportunities to incorporate innovations whilst still remaining compliant with the standard interfaces. Suppliers need to be actively involved in maintaining the set of standards to ensure that the interfaces do not start to constrain innovation as time goes on.

A set of IMA standards which permits supplier innovation will help to establish the product differentiation which is necessary for a more open market to be successful.

The need to support supplier innovation, supplier independence, supplier competition, interoperability, interchangeability and technology transparency suggests that IMA should be based on open standards. Open standards should define an open *generic architecture* in terms of interfaces, building blocks and guidelines so that open *system architectures* can be constructed. The following points constitute a checklist which should help to determine "openness":

1. Information published & publicly available - open access.
2. Sufficient information provided to allow implementation (not reliant on unpublished material).
3. No royalties payable on use of the information - open exploitation.
4. Not dependent on proprietary components or processes.
5. Standards and essential components not restricted by export control regulations.
6. Possible to create special to type items which satisfy the standard interfaces and are interoperable with other items which conform to the standards.
7. Open to technology growth and system growth.

The creation of open standards alone is not enough. It will be necessary to agree how properties such as interoperability, interchangeability and backwards compatibility can be verified. In the short term, the ASAAC Phase II demonstration/validation programme is intended to help by developing this verification process. In the longer term the establishment of approved test houses is one possible answer, but project specific qualification/certification requirements must also be taken into account. The standards must work well together as an integrated set, and the drive to adopt commercial standards which have been originated in isolation could make this a challenging proposition. The standards also need to be maintained as an integrated set over a long period of time, probably requiring the coordination of a number of standardization bodies. Writing and maintaining standards for IMA is a large undertaking, but the payback in LCC makes it all worthwhile.

5.3 Durability of Standards

Assuming that technology transparent standards for IMA are possible, it must be recognized that they will not last forever. It is hard to state a definite life expectancy for IMA standards, but it seems reasonable for them to remain useful for new designs which are initiated during the life of the first project to apply them, i.e. around 40 years. The decision as to when to switch to totally new standards must be based on LCC considerations, principally an understanding of when maintenance of backwards compatibility ceases to be cost effective. Once satisfactory IMA standards have been established, it is hoped that it will be possible maintain their relevance by a process of evolution rather than starting again from scratch with every standard at one point in the future.

Phase I of the ASAAC programme (Reference 1) looked at the problems of writing long term standards and concluded that it would be necessary to base them on a set of well defined interfaces and technology-independent behavioural descriptions. These would have to be supplemented by slash sheets covering technology-dependent parameters which would be issued to establish new minimum acceptable performance levels as time went on, taking care to maintain backwards compatibility. The traditional approach to writing standards usually results in a fundamental link between the required behaviour and specific technologies, requiring totally new standards when a particular technology becomes obsolete or constrains performance. This point is well illustrated by the number of PC motherboard buses which have been introduced over the last 13 years, e.g. ISA, EISA, MCA, VESA Local Bus, PCI, etc. Prospective writers of long term IMA standards therefore need to look carefully at existing standards which have stood the test of time and establish an appropriate approach before rushing into print.

It is important to recognize that the durability of interface standards will vary at different levels in the system, and that this will not be a problem if the set of standards has been carefully planned. For example, it should be possible to define the high level Application to Operating System (APOS) interface (Figure 3) so that it is stable over a long period of time. Future systems will require large amounts of application software, so stability of the APOS interface will greatly reduce software LCC by facilitating reuse and software maintenance. The lower level Module to Operating System (MOS) interface, however, must be tuned to the underlying hardware if it is not to limit the exploitation of more capable technology. The MOS definition may therefore need to be updated every few years to incorporate, for example, new hardware features. This is not a serious problem, as the Module Support Layer (MSL) is provided with each LRM by the manufacturer. An updated operating system can be used which has the new MOS interface features, comparable to the situation with PC operating system upgrades which cater for new microprocessors. The updated operating system must obviously maintain backwards compatibility with existing application software via the APOS interface.

In the data communication network it is the lower level interface which must be the most stable. This is because the optical component of the Module Physical Interface (MPI) is exposed at the LRM connector and must be preserved in order to maintain backwards compatibility of new LRMs in old systems. The higher level Network Independent Interface (NII), which lies at or below the MOS interface, is not so exposed, so that the impact of any enhancements can be handled in the MSL and operating system as described above.

Long term IMA standards must also be written to cater for supplier innovation, i.e. the freedom for building block manufacturers to incorporate novel approaches, methods, processes, materials, devices and technologies in order to improve performance and reduce costs. The capability to allow supplier innovation whilst maintaining interchangeability and technology transparency is an important characteristic of true Integrated Modular Avionics.

6 SYSTEM LEVEL ISSUES

IMA has two major objectives:

- modularity, which means that there is a set of standard elements from which to construct each specific system
- the simplification of functional and physical integration in complex systems

Functional integration is the close linkage of functions which might have been segregated in the past, e.g. flight control and powerplant control, radio frequency/electo-optical (RF/EO) sensor fusion, etc. Physical integration is the sharing of common resources, e.g. racks, modules, power supplies, data networks, etc. IMA does not define how the elements are integrated because the rules used to build a system are different from one system to another. The requirements are likely to be different in terms of mission and operational performance, safety and security, the scope of mission functionality, cost constraints, etc. Each system is a new compromise between all these different aspects, leading to different integration rules.

The goal is to ensure the portability of core elements with minimum redesign, development, requalification when the technology changes (between different systems or inside the same system). Different levels of portability can be considered (for example : specification level, source code, compiled code) depending on what changes in the technology. A universal rule cannot be given for portability.

To ensure the portability of the core elements between systems, interface standards are necessary to clearly identify those elements. However, each element cannot take into account the sum of all possible rules and constraints dictated by each specific system integration. This has always been true in the past and the efficient solution has generally been to take care of the system issues at each specific application level. For example, comparison between two or more channels is a consolidation method which has been used extensively in order to satisfy safety requirements. At the individual channel level the safety requirements may have no additional impact as far as the components are concerned, it is the addition of *consolidation* which is specific. The safety aspects are taken care of at the *application level*, not by the use of particular technologies.

When the technology is relatively simple it might be possible to address such problems at quite a low level, down to the component level. For example, some safety criticality aspects of systems can be taken into account at the transistor level at one stage of technology evolution. When technology complexity increases, it becomes more and more difficult to take the system issues into account at such a low level, and a component by itself might be as complex as a complete system some years before. Continuing the previous example, it does not seem reasonable to take into account all the safety aspects at the transistor level when using complex microprocessors containing millions of transistors. This hardware complexity is of the same level of complexity as the software of an operating system. The capability to control the implementation inside these types of complex components is no longer practical for avionic developers.

When technology changes at a rapid rate without any possibility of controlling the details at the interfaces it becomes more and more important to take care of the system issues at as high a level as possible. The integration rules being different from one system to another, the only possible level is the application level to ensure that the result will be robust at the overall system level. Military avionics now takes its place with nuclear power generation, industrial robotics, and the automotive industries in the need for real time performance and high integrity levels where protection of personnel and property is involved. By analogy with what can be done in other domains than avionics, it should be possible to handle the safety and the security aspects by using encoding, encapsulation and keying techniques. Keying means associating a code with something in order to give it access to an area, much as we use a key to open a door lock or enter a numeric code to gain access to a restricted zone in a building. These techniques have been developed in order to protect a system or its components from being disturbed by external influences or unauthorized use of facilities or information (e.g. encoding satellite communication for acceptable signal to noise ratio, 4-digit code numbers for cash-card withdrawals from bank machines, sending back information for verification).

These techniques are already being used inside systems to address some security aspects. Their use could be increased to encapsulate each element of a system, to control propagation of data inside a system, to protect data in restricted zones of a system (memory areas for instance), and to create firewalls between different areas of a system. The use of encoding, encapsulation and keying techniques in an avionic system is starting to become possible because of the rapid improvement of the computation and communication capabilities of emerging technologies. Up to now, optimization has always been necessary because of the low capabilities of technology compared with functional needs. Extra overhead was not affordable. However, emerging technology offers plentiful computation power, transmission bandwidth, etc. and could absorb the overhead whilst remaining affordable in terms of volume, mass and cost. Encoding, encapsulation and keying techniques can be extrapolated to safety and security in general in conjunction with the overall fault detection and isolation techniques.

The application of techniques which support technology transparency will require new methods for the design and development of systems. It will also require the re-examination of system qualification and certification procedures. The applications, and more particularly the system management applications will need to take into account the implementation of encoding, keying and other techniques from the very beginning. The codes and keys will have to be adaptable to each specific system implementation.

7 COTS

In order to better control the cost of the systems, the end users are more and more asking for Commercial of the Shelf (COTS) technology. The market drives COTS standards and components to deliver performance and a quick return on investment; technology transparency is not an objective.

The military niche market has been using COTS technology for many years, but always with appropriate ruggedization to meet the demanding military physical and operational environment. Some examples include the large range of electronic parts, e.g. processors, memory, ASICS, etc., which use commercial semiconductor die, and at the appropriate production stage are routed down a ceramic packaging line instead of plastic, with appropriate military Quality Assurance (QA) controls applied. Other examples are the ruggedization of flat panel displays for cockpits and fibre optic technology from the telecommunication industry for installation and use in military aircraft systems. Looking ahead, there is no serious alternative to meeting military avionics mission requirements other than using components which have been developed for the commercial market. The competitive commercial market forces make for continual advances in computing and I/O and graphics performance, and good parts gain world-wide usage. The use of ruggedized COTS parts under controlled conditions will therefore continue to be the norm within the military avionics industry.

The trend is now towards applying even more COTS technology in the defence industry, and the requirements remain just as strong for ensuring that each type of COTS technology, which includes software products, can be sufficiently ruggedized for military usage. Most aerospace companies have past experience of apparently cheap COTS technology failing to meet qualification requirements at a crucial stage in the programme.

The most important challenges of using COTS are:

1 Ensure the parts meet the environmental requirements (i.e. both the physical environment and the software engineering environment as appropriate) and make sure that the requirements are not over specified.

2 Ensure the selected parts have a reasonable lifetime expectation, bearing in mind military equipment lifetimes are of the order of 25+ years whereas commercial parts lifetimes are typically 5 years and tend to be getting shorter as technology innovation accelerates. Understand how obsolescence will be handled.

3 Be very careful when using COTS software, its documentation and associated licensing, since it is difficult to maintain a military product with COTS software embedded.

4 The unique combination of constraints and requirements which military aircraft must satisfy dictate that the level of COTS usage will be within modules, not the modules themselves.

Point 2 is typically a technology transparency problem where techniques as described in the previous paragraphs have to be used.

For point 1 new compromises will need to be studied when building a new platform or the installation of a new system inside a platform. The two main reliability drivers for electronics components are temperature and vibration.

For cooling, new implementations are being considered including liquid cooling to improve the performance of the environmental control systems. The compromise is between system reliability, additional mass, volume and complexity of platform, LCC. In fact the overall environmental control system needs to be redesigned with new criteria ; for example the COTS range of temperature is much smaller than the military aircraft environment range of temperature at high temperatures, but also at low temperatures.

For vibration, active reduction (active anti-vibration mounting) is being considered.

In all cases, the overall environment of the electronics inside military aircraft will have to be improved.

There are several ways to consider the level of COTS inside a module:

- Today it is considered at the component level. Ruggedization is done at this level, by using ceramic casing instead of plastic, for example.

- When complexity increases, it is necessary to handle the problem at a higher level. It is not possible to have a complete COTS module because it will not be compliant with the single standard interface. However, it might be possible to handle it at the next lower level which is the board level. For example, if a processing board is a COTS item, then a module can contain in addition another board for conversion to standard power levels and to standard networks. The two boards can be encapsulated in a single packaging with standard connectors. The packaging by itself will be the EMC and physical handling protection of the COTS electronics. The physical encapsulation technique gives:

  - a standard physical interface
  - protection from the environment (which is improved compared to the existing environment)
  - minimum design and development for the adaptation between COTS and standard interfaces. For example, if a COTS electronic board can be used inside a standard LRM with an additional internal interface inside this LRM between the COTS board and the standard LRM power supply and network interfaces, then when the COTS board technology changes the only redesign necessary should be for the internal interface. This should constitute a very small part of the LRM.

Module format will have to be adapted to these techniques and be able to incorporate commercial board formats. The trend will not be to integrate as much electronics as possible on smaller formats, as has been the case in the recent past (e.g. : SEM E format).

8 SYSTEM DESIGN TOOLS

So far, technology transparency has been considered in relation to systems and system building blocks, but it is also important for the tools which are used in the system design process.

The initial dilemma is whether to develop proprietary design tools or use what is commercially available. Proprietary tools have the advantage that they can be made entirely compatible with the originator's system design process. However, the cost of developing and supporting an integrated toolset over the full lifecycle of a military project can be enormous.

The market for commercial tools is developing rapidly, leading to more and more products and suppliers. Although market forces should help to keep the acquisition and support costs for commercial tools within acceptable limits, it is difficult to maintain an integrated toolset which covers the full lifecycle. Examples of the problems posed by the adoption of commercial tools include:

- Difficulty in interfacing tools from different suppliers due to lack of standardization, resulting in custom solutions for data interchange. The trend towards multi-company integrated teams adds a new dimension to this problem.

- Dependency on single-source suppliers, who may go out of business or discontinue support for a particular tool.

- The need for tools to support project datasets with a very long lifetime.

- Rapid development of the computing technology on which the tools run, leading to obsolescence.

There are clear similarities between these four problem areas and factors which are important for systems and system building blocks, i.e.:

- Interoperability
- Interchangeability
- Backwards compatibility
- Technology transparency

It should therefore be possible to tackle these toolset problems using the techniques which are being applied in IMA. Open standards for tools are required to define the interfaces which allow tool behaviour to be encapsulated and described independently from the implementation technology.

9 CONCLUSIONS

- Obsolescence is a major problem, therefore technology transparency must be addressed at the requirements stage.
- IMA standards are required in order to ensure that technology transparency is embodied in IMA products. IMA requires *open standards* which are endorsed and actively supported by industry and governments, allowing long term *open systems* to be implemented based on OTS (Off The Shelf) building blocks.
- Technology transparency is important for system design tools as well as system products, and can be tackled using the same techniques.
- Technology transparency leads to inefficiency, but we are at the crossover point NOW with an increasing abundance of resources in processing and memory. The networks area is a little further behind in terms of bandwidth and latencies, but is catching up. (See Figure 4.). Effectiveness is more important than efficiency.

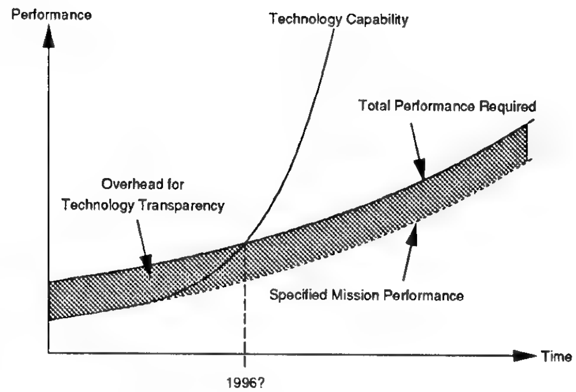

Figure 4: Technology Transparency Crossover Point

- Technology transparency is possible, but the rapid rate of technology development means that it is difficult to give guarantees.
- The holy grail of technology transparency is achievable, but the market needs to be lead in the right direction by standardization programmes such as ASAAC.

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Integrated Modular Avionics Architecture Concepts Demonstration

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1. SUMMARY

This paper reports on the refinement, demonstration and validation of a number of key concepts for Integrated Modular Avionics (IMA), as performed under the IMA Demonstrator programme. For the communication network, software architecture, and fault management areas, selected aspects of the concepts were refined, and implemented on a demonstration platform. This platform, termed the IMA Demonstrator, is a tool for investigating and evaluating IMA issues, and has been constructed largely from commercial off-the-shelf components. In the IMA Demonstrator, the communication network is implemented by a functional prototype of the Matrix Switched Network. The software architecture of the IMA Demonstrator includes functional prototypes of the communication system and the fault management system. The IMA Demonstrator and its functional prototypes have been used to validate the relevant IMA Concepts.

2. INTRODUCTION

2.1. Integrated Modular Avionics Concepts

Integrated Modular Avionics (IMA) systems are recognised as providing an answer to the requirements and constraints of modern military aircraft. According to the IMA concept, a system implementation is built up from hardware modules and software components with standardised interfaces, according to a set of guidelines. In comparison with the previous generation of federated avionic architectures, the benefits provided by IMA systems will include improved fault-tolerant operation, leading to improved operational and mission performance, as well as a greater openness to growth and innovation, and a reduction of life cycle costs.

IMA concepts may be broken down into the following areas:

- Software Architecture
- Communication Network
- Fault Management
- Common Functional Modules
- Packaging.

2.2. Areas of Investigation

From the key areas mentioned above, the first three have been selected for investigation under the IMA Demonstrator activities reported upon in this paper. While all of the areas are inter-dependent, the Software Architecture, Communication Network and Fault Management concepts are particularly closely related, and are suited to investigation largely independently of the development of dedicated hardware. National and international programmes, including in particular ASAAC Phase I (Ref. 1) and EUCLID / CEPA 4 / RTP 4.1 (Ref. 2) provided the basis for the IMA concepts to be investigated. The IMA Demonstrator programme is performed in co-operation with a number of German avionics and aircraft companies.

The IMA Network Concept

The overall IMA network concept provides for communication between the modules and other equipment of the IMA system, and requires the specification of a Network Independent Interface (NII) and a Network Protocol Stack, as shown in Fig. 1. The NII ensures that the implementation of the network is decoupled from that of the operating system (shown as the network user). The specification of a protocol stack based on a defined model ensures that modules are able to communicate with one another. The circuit-switched Matrix Switched Network (MSN) is proposed for the relevant protocol layers.

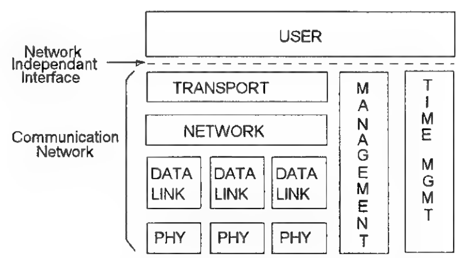


Fig. 1: Communication Network Model

The IMA Software Architecture Concept

The two main components of the software architecture concept are the use of two well-defined interfaces and the Blueprint Concept, as shown in Fig. 2. The two interfaces defined are the Application to Operating System interface (APOS) and the Module Support Layer to Operating System interface (MOS). Blueprints provide a logical description of the system and define its mapping onto the system resources. Together, the defined interfaces and the blueprints support the independence of the software from the hardware, providing for software re-usability and for the development of hardware and software to accommodate system growth.

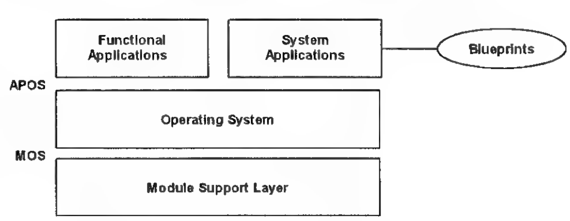


Fig. 2: Software Architecture Layer Concept

Paper presented at the AGARD MSP Symposium on "Advanced Architectures for Aerospace Mission Systems", held in Istanbul, Turkey, 14-17 October 1996, and published in CP-581.

The IMA Fault Management Concept

A fail-operational concept ensures that on the occurrence of a failure the system performs real-time reconfiguration, if necessary, to allow the function suffering the failure to continue to be performed. A wide variety of reconfiguration mechanisms might be used, including, for instance, hot stand-by components with full functionality, and cold stand-by components with degraded functionality. On the detection of failures by the health monitoring services of the operating system, a system application refers to the reconfiguration strategy stored in the blueprints in order to reconfigure the system.

Concept Refinement

Selected aspects of the three key concept areas under investigation have been refined to a stage at which they may be demonstrated and validated on the IMA Demonstrator.

For the communication network, the concept for the implementation of the network lower layers was refined. Simulation and modelling of a number of alternative networks was performed, and the selection of the MSN as the preferred candidate confirmed. The MSN concept was then developed further, and the requirements for the accompanying higher-level protocol investigated.

Under the software architecture, concept refinement addressed the communication system, which supports all forms of communication within the IMA concept, and the fault management system. The Blueprint Concept was developed to provide the support required by the communication and fault management systems.

Comparison with other Models

The IMA concept models show many similarities with other contemporary open system architecture models. Figs. 3 and 4 attempt to show the relationship between the IMA communication network and software architecture concepts and the following models:

- IEEE POSIX Open Systems Environment (OSE) standards (Ref. 3)
- SAE Generic Open Architecture (GOA) framework (Ref. 4)
- ISO Open System Interconnect (OSI) Model (Ref. 5)
- French MoD Reference Model, GAM-T-103 (Ref. 6).

In comparison with the other generic models, the IMA concept includes some special features for the real-time avionics application, such as the Blueprint Concept in the software architecture concept, and the Management and Time Management services of the communication network concept. Further discussion of the comparison of the models is included in Ref. 7. Fig. 3 shows the relationship between the communication models.

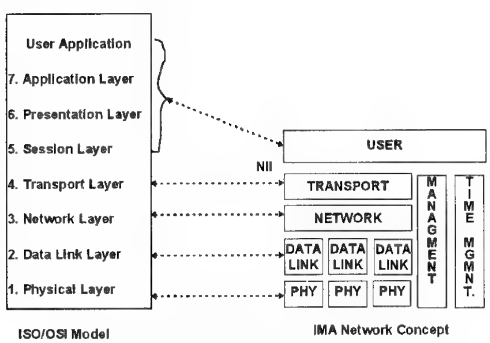


Fig. 3: Communication Models

The structure of the IMA communication network may be mapped onto the four lower layer of the ISO/OSI reference model as shown, and also corresponds directly to that of the GAM-T-103 standard.

Fig. 4 shows the relationship between the software models.

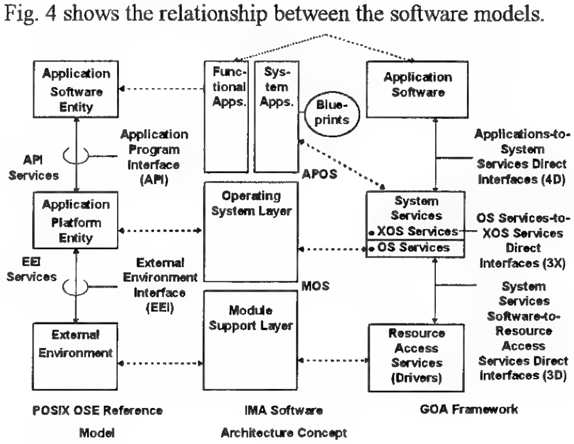


Fig. 4: Software Architecture Concepts

2.3. The IMA Demonstrator

The IMA Demonstrator is a system for the development, demonstration and validation of IMA concepts. In its initial form, as described in this paper, it is being used for the demonstration and validation of the concepts addressed in the previous section, for which functional prototypes of the relevant components of the communication network, software architecture, and fault management system have been constructed. In order to concentrate efforts on the demonstration of the particular concepts of interest, these have been implemented, as far as possible, on the basis of standard commercial hardware and software. Following the development of functional prototype components and their integration into the IMA Demonstrator system, an evaluation is being performed, which is to be concluded with the demonstration of a functional chain for a representative avionics application.

The IMA Demonstrator is designed to provide for growth in its functionality and the substitution of more mature components as these become available, in order to provide continuing support for the development and evaluation of the IMA concepts.

The IMA Demonstrator architecture is shown in Fig. 5.

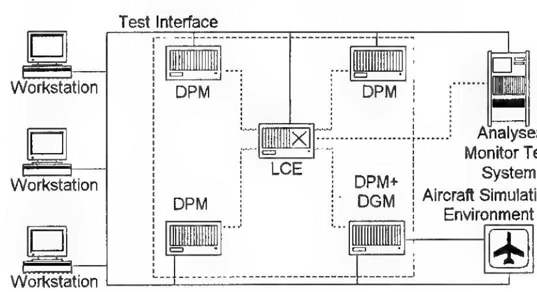
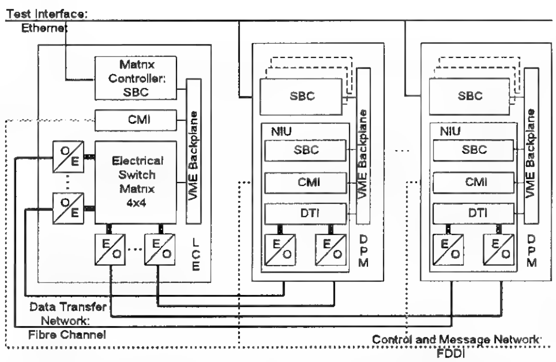


Fig. 5: IMA Demonstrator Architecture

The components of the IMA Demonstrator may be divided into two categories. The Demonstration Components implement the concepts to be demonstrated, and are shown in Fig. 5 within the broken box. The second category is the Demonstration Support Components, on which the software is developed, and which provide control and analysis

facilities for the demonstration. Most components consist of both software and hardware.

The essential hardware Demonstration Components are shown in more detail in Fig. 6.



LCE	Link Control Element	CMI	Control and Message Interface
DPM	Data Processing Module	DTI	Data Transmission Interface
SBC	Single Board Computer	FDDI	Fibre Distributed Data Interface
NIU	Network Interface Unit		

Fig. 6: Hardware Demonstration Components

- *Data Processing Modules (DPMs)*

  The DPM functional prototypes are implemented as VME racks holding one or more commercial PowerPCs, together with a Network Interface Unit (NIU), which provides the interface to the communication network, and which also consists of off-the-shelf hardware.

- *Link Control Element (LCE)*

  The LCE functional prototype performs the role of switching in the Matrix Switched Network (MSN) implementation of the communication network. The LCE is also implemented as a VME rack, holding a custom electrical switch matrix board, a commercial PowerPC single board computer, and other off-the-shelf interface components.

- *DGM (Digital Graphics Module)*

  Following the evaluation of an initial IMA Demonstrator configuration as shown in Fig. 6, a DGM functional prototype will be added to the system by integration into the backplane of a dedicated DPM, in order to evaluate a representative avionic functional application.

The Demonstration Support Components support the development of software components, software loading, demonstration control and monitoring, and test evaluation. They are based largely on standard commercial products, and comprise the following:

- *Workstations*

  These are standard Sun Sparc workstations, and act as hosts for the Apex Ada development environment.

- *Analyser Monitor Test (AMT) System*

  The AMT provides analysis, monitoring and test facilities for the system, and is comprised largely of specially developed components, due to the specific features of the IMA Demonstrator.

- *Aircraft Simulation Environment*

  The aircraft simulation environment is added to the IMA Demonstrator for the functional demonstration to be performed with the DGM, in order to provide for dynamic system evaluation under operational conditions.

The IMA Demonstrator components are interconnected by the test interface, which is implemented as an Ethernet network, and provides for data transfer for demonstration setup, control and analysis.

3. CONCEPT DEMONSTRATION

3.1. Communication Network Concept

3.1.1. Requirements

In comparison with previous generations of system architecture, Integrated Modular Avionics systems will impose considerably higher data transfer requirements. These requirements, for communication between modules and with other equipment, within and between racks, are to be fulfilled by the communication network.

A number of requirements on the communication network derive from the overall IMA aims and concepts. The splitting of processing functions which were previously contained within single equipments and the accompanying earlier digitisation of sensor data give rise to a considerably greater total data transfer volume, with higher data rates per connection. In addition, the system requirement for fault-tolerance demands that the network supports a high level of mobility of software functions within the system architecture. The overall IMA aim of module interchangeability leads directly to the requirement that the communication system provides standardised interfaces and operation. The communication network must, like the rest of the IMA system, provide technology transparency, and must provide for the application of commercial off-the-shelf (COTS) technology. The network should also be scalable, to provide for varied applications, and should provide for growth within a particular application. Finally, a universal solution for all network communication requirements is desired, in order to avoid the proliferation of different hardware and software.

The current performance requirements are derived from the anticipated data transfer requirements of the first IMA applications: growth capacity should enable the communication network to meet the more demanding requirements which will subsequently arise for later applications. While the requirements of the various data transfers within the system are very wide ranging, an attempt is made here to summarise the driving requirements.

A maximum of 256 network ports is required. The required maximum data transfer rate is 2 Gbit/sec, in order to accommodate digitised sensor data and uncompressed high definition video. The maximum time to establish a physical connection between a source and sink, which is referred to as the linking time, is 10µs. The maximum data latency requirement is generally 100µs, but only 1µs in the case of some sensor data. In order to support the fault-tolerance of the overall system, the communication network is therefore required to provide fault-tolerant operation itself.

A number of available and developing network technologies have been investigated as possible solutions to these requirements, including the Asynchronous Transfer Mode network, ATM, the Scalable Coherent Interface, SCI, and Fibre Channel. As none of these was considered likely to be able to offer a very well optimised solution to the IMA requirements in the relevant timescales, a solution was sought which, while making use of COTS and other available technology, was more suited to fulfilling the IMA requirements.

3.1.2. The Matrix Switched Network

The concept developed in response to these new demands is that of the Matrix Switched Network (MSN). The MSN comprises a high speed circuit-switched Data Transfer Network (DTN) component, complemented by a Control and Message Network (CMN) component based on a technology such as a data bus or a packet-switched network. DTN

signalling information, in the form of circuit control commands, is transmitted by the CMN, and circuit switching performed by an Optical Switch Matrix. The DTN component is used for the carriage of the streaming-oriented sensor data. For such data, a connection is likely to be established on entering a system mode or configuration, and to remain in use until the system is re-moded or reconfigured, a period of many seconds. In addition to the commands for the switching of the DTN, the CMN component also carries user message data. CMN messages will generally be smaller than those transmitted via the DTN, and the paths they take are likely to vary over a fairly short timeframe.

The basic structure of the MSN is shown in Fig. 7. The Link Control Element (LCE) lies at the centre of the network, and consists of a non-blocking Optical Switch Matrix, a Matrix Controller, and an interface to the CMN. MSN users are connected to both network components.

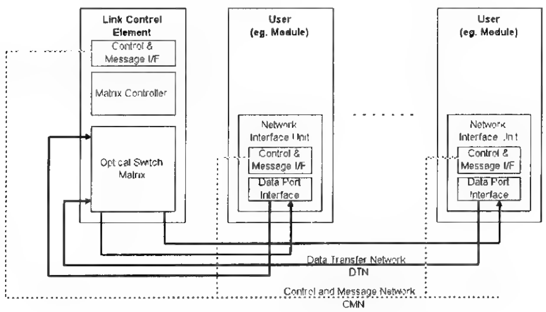


Fig. 7: Matrix Switched Network

In order to transfer data over the DTN, an MSN user initiates a request for a DTN connection to another user by transmitting a request for a physical connection over the CMN to the LCE. If the LCE is able to meet the request, it switches the Optical Switch Matrix to provide the physical connection, enabling the two users to communicate with each other. It must be ensured at the system design time that the DTN topology is able to support the required system application configurations. While the connection remains in existence, the LCE takes no further part in the communication, and has no access to the data being carried on the DTN. In addition to point-to-point physical DTN connections, with a suitable choice of Optical Switch Matrix architecture, multicast can also be achieved, and multiple data streams may also be multiplexed over a single DTN connection.

When user data is transmitted over the CMN, only the CMN component is involved.

The implementation of both network components will be based on a current version or derivative of an existing network standard. The DTN would use parts of the physical layer and frame structure of a network such as Fibre Channel, or possibly elements of SCI or ATM, while candidates for the CMN would include the SAE Linear Token Passing Bus (Ref. 8), FDDI (Ref. 9), SCI (Ref. 10), in its forthcoming real-time version, or ATM.

Where required, for instance due to its total data flow requirements, a network user equipment may be equipped with more than one DTN interface. On the other hand, some additional network users whose data transmission requirements may be fulfilled by the CMN alone may be connected only to this component. Systems may be built up of multiple LCEs, with each LCE interconnected by DTN and CMN links, as shown in Fig. 8.

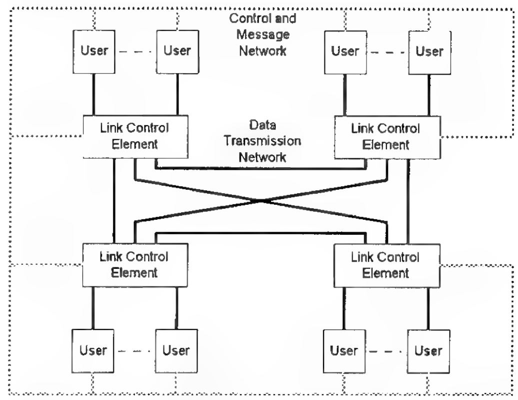


Fig. 8: Example MSN Architecture with Multiple LCEs

MSN Protocol Layers

The protocol model used for the definition of the MSN is shown in Fig. 9. It is based on the ISO/OSI model (Ref. 5), modified for real-time use by the removal of the top three layers beneath the application, and the addition of Management and Time Management services.

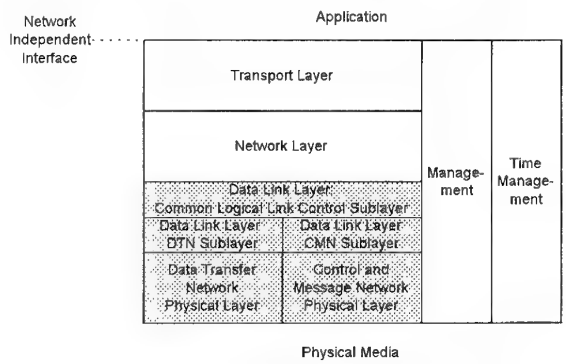


Fig. 9: Communication Network Protocol Structure

In terms of the above model, the MSN includes the Data Link Layer and the Physical Layer, shown shaded in Fig. 9. As depicted, each of the network components includes its own physical layer, and lower data link layer sub-layer, which includes any medium access control functions required by the CMN. The MSN provides a single Logical Link Control (LLC) sub-layer, which performs the medium access control function for the DTN with the support of services provided by the CMN. The LLC integrates the functionality of the two MSN components to provide a single set of network services to the layer above, which provide for both DTN and CMN transfers. The services are based on those of the standard ISO 8802-2 Local Area Network LLC (Ref. 11). Both connection-mode and connectionless-mode services are offered, the former being more suited to streaming data to be carried over the DTN, and the latter to the system control and message data to be carried over the CMN.

In systems consisting of multiple LCEs, a meshed network would be used between the LCEs, providing a number of different possible DTN routes between a given pair of source and destination Network Interface Units (NIUs). The LCE to which the transmitting NIU is attached performs a routing function, determining the step-by-step route to be set up between the various LCEs, and requesting the establishment of this path by the use of CMN messages. A network management protocol periodically supplies each LCE with the network state information for the complete network, this being feasible due to the limited size of even a relatively large avionics network.

There are a number of possible techniques which may be adopted in order to offer the required fault-tolerance in the MSN. Redundancy in the paths between the LCEs will be provided by the meshed network, and additional LCEs and paths could be added to increase the number of routing options. Further, the number of different possible DTN routes between a given source and destination NIU may also be increased by the provision of multiple interfaces on network user equipment. The routing process will have to be designed according to the particular techniques chosen.

Comparison with Alternative Networks

Of the potential alternative networks to the MSN, two of the most relevant are ATM and SCI. Each of these was originally devised for a particular area of application which differs significantly from an IMA system, leading to certain limitations in their applicability to an IMA system. These two network technologies have been assessed and compared with the MSN using simulation and analytical techniques.

ATM is a connection-based fast packet-switching technology aimed in the first instance at wide area networking applications, in which it is achieving a high and ever-growing level of acceptance. Current restrictions on the application of ATM to IMA include the overheads of the connection set-up procedure on the transfer of randomly-directed control and message data, and the reliance of the capacity reservation procedure on a more stochastic data generation process than those of the streaming sources of an IMA system. Further reservations regarding the adoption of ATM relate to the significant risk associated with upgrading the technology to the required data rates, and the current lack of market openness due to the incompatibility of commercial implementations.

SCI is a register-insertion-ring-based technology proposed primarily for closely-coupled multiprocessing applications, which also supports longer-distance communication. The basic ring topology offered is, however, of limited suitability to the IMA application, and the development of the necessary high-speed SCI packet switches is still at relatively early stage. The required real-time version, featuring prioritised transmission and fault-tolerance features, remains at the discussion stage, with industrial commitment not yet secure.

While the MSN is not in itself a COTS network, fully COTS versions of ATM and SCI cannot be used in an IMA system, as discussed above. The MSN does, however, make use of COTS network technology to provide a communication network tailored to real-time distributed systems, with two complementary components for streaming and message data. It might, for instance, employ an SCI implementation as the CMN, or use SCI technology by adopting its frame structure for the DTN component. Another technology with which the MSN would be compatible is Wavelength Division Multiplexing, which would in the future offer an upgrade path to greatly extend the network capacity

Higher-Level Protocol

Returning to Fig. 9, the application requires a high quality end-to-end communication service with a guaranteed quality of service, offering such features as end-to-end control, error control, flow control, segmentation and reassembly, and multiplexing and demultiplexing. This service is provided by the Higher-Level Protocol, which sits above the MSN, and which might be split into the Transport Layer and the Network Layer, as shown.

The requirements for the higher-level protocol for the communication network correspond with those set down by the SAE for such an application (Ref. 12). These differ from those for a typical OSI system due largely to the real-time nature of the IMA application and its strict fault-tolerance requirements. For the IMA application, these factors result in the implementation of fault-tolerance features at a lower protocol level in hardware, and consideration of the use of a single protocol layer rather than the OSI-based Transport and Network layers. The types of service to be provided by the higher-level protocols include connection-oriented and connectionless data transfer, including multicast; time management, including synchronisation; and management services including configuration, monitoring, control, and test. It should be possible to fulfil the requirements by adopting, and modifying if necessary, a current version or future development of such real-time protocols as the GAM-T-103 series or XTP (Ref. 13), or possibly a development of OSI TP4 or TCP/IP.

Whichever basis is used for the higher-level protocol, the interface between the higher-level protocol and the application will be standardised, as the Network-Independent Interface (NII). This will contain a parameterised specification of the quality of service, and so de-couple the application from the network implementation, allowing future advances in the network technology to be exploited by the application.

In terms of the IMA software architecture concept (see Sec. 3.2), the NII is a component of the MOS. It forms part of the interface between the communication network, which is implemented in the Module Support Layer and network-specific hardware/firmware, and those communication functions of the Communication System which are common to both internal and external module communication, which are implemented as part of the Operating System Layer.

3.1.3. Concept Demonstration

In order to validate the MSN concept, an MSN functional prototype is being demonstrated as part of the IMA Demonstrator. The implementation is based on commercial standards and components, as far as possible, and an electrical switch matrix is used. The DTN physical layer and frame structure is based on an implementation of Fibre Channel, and the CMN is implemented as an FDDI network. The main MSN features are implemented in the demonstrator as follows:

- Network topology comprising two complementary components, ie. circuit-switched DTN and token ring-based CMN.
- Functional prototype Logical Link Control (LLC) level protocol.
- Provision for multiple NIUs per DPM for redundancy purposes.
- Compatibility with the message-passing scheme of the software architecture concept.
- Framework for a Network Independent Interface.
- Demonstration performance targets for Data Rate, Latency, Linking Time.

A 4x4 LCE has been built, together with four NIUs. The DTN component uses a FibreExpress Fibre Channel implementation with a multimode electro-optical converter to provide a peak data rate of 400 Mbit/sec, while a 100 Mbit/sec Interphase single-attached FDDI implementation and concentrator are used for the CMN. The LCE comprises a custom board carrying a TriQuint electrical crossbar switch and electro-optical converters, together with a single board computer and FDDI interface with the matrix controller software. Each NIU consists of a VME-based Fibre Channel interface and a single board computer and PCI Mezzanine Card FDDI interface with the LLC software, and interfaces with its host via a VME interface.

As a first stage in the integration of the network, a self-contained MSN Prototype System has been built, consisting of an LCE, and four NIUs in one rack driven by one single board computer. This is to be used to conduct functional tests, and performance tests addressing such key parameters as throughput, transfer latency, linking time and error and loss rates, from which the results will be assessed against the design parameters. After completion of tests on the MSN prototype system, the individual NIUs will be removed and distributed to and integrated into the three DPMs of the IMA Demonstrator, giving, together with the LCE, the configuration shown in Fig. 6. The IMA Demonstrator will then be used for further demonstration, as described in Sec. 4.

Following the completion of the current concept validation work, it is planned to continue the development of the MSN with the support of the IMA Demonstrator. Proposed developments for the short-term include developing the Logical Link Control protocol sub-layer to include fault-tolerance, to add inter-LCE routing, and to improve its performance. The optimal choice of network technology for the CMN should be kept under review, as should the development of the technology for the optical switch matrix, and, when this is sufficiently well advanced, the electrical switch of the LCE should be replaced by an optical version. The definition of the Network Independent Interface should be developed, and the suitability of the candidate higher-level protocols investigated.

3.2. Software Architecture Concept

3.2.1. Requirements

It is one of the aims of Integrated Modular Avionics that whereas systems should be open to the introduction of new hardware in much shorter cycle times than with previous generations of federated avionic systems, IMA software systems should remain in use over a longer timeframe than with the previous project-specific software systems. This results in the need to adapt the avionic software system more frequently to new hardware environments, for instance with the introduction of new processors or new communication networks, for instance to achieve performance improvements or to replace obsolete components. The resulting requirements for software portability and re-usability both contribute to lowering life-cycle costs, and are two of the driving requirements on the IMA software concept. A further driver is the requirement to perform fault-tolerance on a hard real-time system potentially subject to flight- and mission-criticality constraints.

The use of the layered structure of the IMA software architecture shown in Fig. 2 enables the fulfilment of the requirements for portability, re-usability and fault-tolerance.

The high level Application to Operating System (APOS) interface is implemented by a set of Operating System Layer (OSL) services which allow the Functional and System Applications to access the distributed Operating System software, including:

- Transparent communication services, via virtual communication channels
- Resource mapping and (re-)configuration services
- Fault detection and isolation services.

These operating system services provide lower-level support to the System Applications which provide the actual system management functionality, for such functions as the reconfiguration of resources and applications.

To ease the integration of new hardware into the system, a standard interface is introduced below the operating system. The Module Support Layer (MSL) implements hardware-dependent functions which support the operating system. By defining and standardising the MSL to Operating System (MOS) interface, the effects of changes in the hardware may be restricted to the MSL. The Network Independent Interface of the communication network will form part of the MOS.

Blueprints represent a structured description of the avionic system. The Application Blueprints contain the description of the application from a logical point of view, including, for example, the resource requirements and the virtual communication channels. The physical aspects of the avionic system, such as the processors and physical communication channels, are described in the Resource Blueprints. The mapping between physical and logical descriptions is provided by the System Blueprints, in which, for example, the applications are mapped onto processors. Changes in the underlying hardware and related MSL are accommodated by modifying the blueprints.

According to the concept as implemented in the IMA Demonstrator, the mapping represented in the system blueprints is a static mapping, determined at system design time. In the future, it should be possible to extend this to implement dynamic mapping, determined during run-time, while retaining the basic blueprint structure. In this case, the system blueprint would contain mapping rules which would be applied at start-up and during run time to the application and resource blueprints, in order to determine the mapping to be used.

The blueprints and the well-defined APOS and MOS interfaces implement a virtual system concept, which ensures that as many system control tasks as possible are performed in a project-independent and implementation-independent manner. This strategy contributes to fulfilling the IMA objectives throughout the system life-cycle. During system development, it minimises the costs of tailoring the IMA system to a project-specific implementation. During subsequent modification and extension of the system, the system engineering effort is reduced by the software portability and reusability achieved.

3.2.2. Communication System

Concept

The IMA communication system must be capable of fulfilling the IMA requirements for the transfer of large volumes of high rate real-time data, between both applications distributed between processing modules, and the various external components such as sensor front ends and displays.

One of the main features of the IMA communication software architecture is the provision of virtual communication channels between the applications, in order to perform communication independently of the current realisation of the physical communication channel and its protocol.

Fig. 10 shows the communication-related aspects of the software architecture concept.

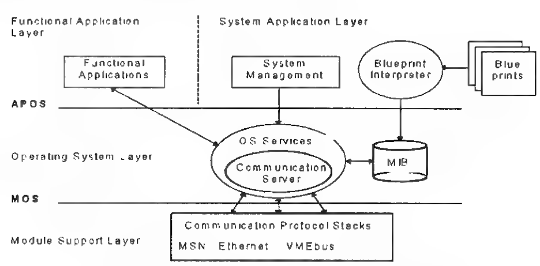


Fig. 10: The Communication System

Demonstration

The Communication Server implements the Operating System Layer services of the communication system; three groups of services have been implemented.

The first group of services relates to connection establishment. The virtual connections will usually be pre-defined in the blueprints, and so such connection services as "define_connection" and "request_disconnection" will be executed by the communication system at system start-up, mode-change or during reconfiguration following the occurrence of a failure, on the basis of the information in the blueprints. During normal operation, the applications will use the pre-defined connections by means of the "use_connection" service.

A group concept, derived from the Message Passing Interface standard (Ref. 14), is implemented in the second set of communication services. These services allow the management of groups of virtual communication channels, which is of great use in implementing a fault-tolerant concept. In order to activate communication to a stand-by module, for instance, the only action to be performed would be to add the connection to or from the stand-by module to the communication group. Messages would then be sent or received automatically by the new group member without explicitly notifying the other applications involved.

The last group of communication services includes the standard well-known data transfer services, such as "send" and "receive". An additional service included is the atomic multicast service, where atomic implies that either all or none of the recipients will receive the message. This service is implemented by the group concept described above. It is mainly used by the fault and configuration manager, and allows the delivery of reconfiguration information to a distributed system, as well as keeping the configuration information consistent.

The integration of the communication aspects of the blueprints into the communication system software has been performed by the use of a Management Information Base (MIB). A Blueprint Interpreter reads the blueprints only once at system initialisation time, following which the MIB provides access to the blueprint information during run-time. This use of this concept simplifies the alteration of the blueprints during the test and system integration phases.

Fig. 11 shows a very simple communication scenario between two applications. It is used to demonstrate the implementation of the communication aspects in the blueprints. The communication between applications is shown from a logical point of view.

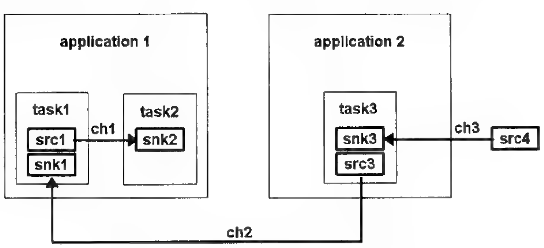


Fig. 11: Example System - Logical Description

Fig. 12 shows the communication aspects of the corresponding application blueprint for Application 1: that for Application 2 would be similar.

```
begin
   name          :=    application_1;
   ...
   begin_app
      begin_com
         ch1              :=    (src1, snk2);
         task1            :=    (src1, snk1);
         task2            :=    (snk2);
      end_com
      ...
   end_app
end
```

Fig. 12: Example System - Application Blueprint

Fig. 13 shows the hardware block diagram of the example system, depicting its physical organisation.

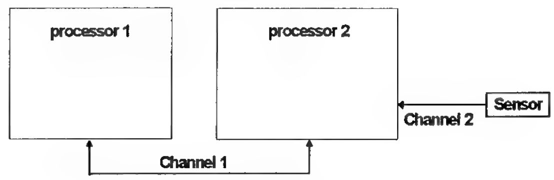


Fig. 13: Example System: Hardware

Part of the physical organisation is described in the resource blueprint as shown in Fig. 14.

```
begin
   name          :=    resource_1;
   ...
   begin_res
      begin_channel
         id     :     channel1;
                ...
         id     :     channel2;
                ...
      end_channel
      begin_proc
         id := proc1;
            ...
         id := proc2;
            ...
      end_proc
      ...
   end_res
end
```

Fig. 14: Example System - Resource Blueprint

The elements of the application blueprints (eg. applications, virtual communication channels) have to be mapped onto the available resources. For the example system, Fig. 15 shows the physical distribution of the applications on processors, and the connections via the physical channels.

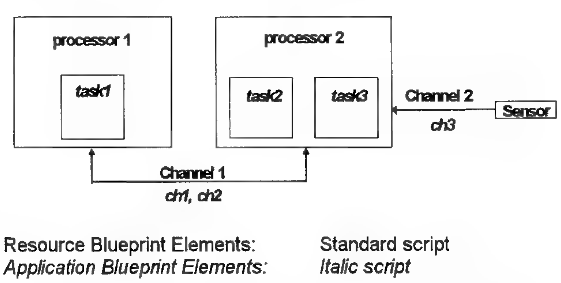


Fig. 15: Example System - System Distribution

The physical representation, ie. the mapping of the Application Blueprints onto the Resource Blueprints, is described by the System Blueprints, as shown for the example system in Fig. 16.

```
begin
    name          := example_system;
    ...
    begin_sys
        begin_proc
            task1                    :=  proc1;
            task2                    :=  proc2;
            task3                    :=  proc2;
        end_proc
        begin_com
            application_1.ch1        :=  channel1;
            application_1.ch2        :=  channel1;
            application_2.ch3        :=  channel2;
        end_com
    end_sys
end
```

Fig. 16: Example System - System Blueprint

In conclusion, the implementation of the communication system using the virtual channel concept and communication information derived from blueprints has demonstrated a concept which supports hardware portability and software re-usability.

Following the completion of demonstration of the implemented services, it is intended to assess the additional overhead imposed by the communication system in relation to the time taken to transfer messages over the underlying communication channel, and to investigate the introduction of prioritised channels in order to minimise its possible consequences.

3.2.3. Fault Management System

Concept

One of the prime requirements on the IMA system is that it provide continued operation in the presence of faults.

Fig. 17 indicates the fault management-specific aspects of the software architecture concept.

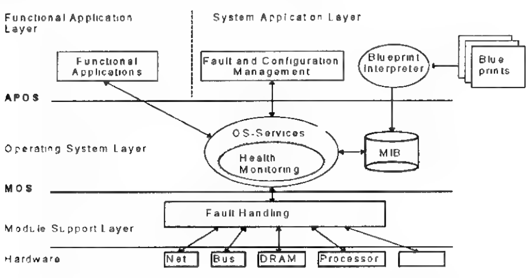


Fig. 17: The Fault Management System

The main services of the IMA fault management system may be broken down as follows:

- System Monitoring and Diagnosis
- Fault Detection
- Fault Isolation
- Fault Recovery.

System Monitoring and Diagnosis services determine the status of the system components by a combination of active testing and passive data collection and evaluation. An example of active component testing is the self-test logic of a hardware clock. In the passive process, information about the system behaviour is gathered, and then evaluated, in order to assess the state of the components, for example by monitoring the processor throughput in order to detect system overload. These services will largely be implemented as Built-In Test services in the Module Support Layer.

Fault Detection services are concerned with determining when a failure has occurred in the system. Fault Detection services request the status of system components from the System Monitoring services, and compare it to the specified system behaviour.

Fault Isolation services attempt to determine the location of the faulty component and to disable and segregate this component from the rest of the system. They also inform the Fault Recovery services of the faulty component and its detected health status.

Both the Fault Detection and Fault Isolation services are supplied by the Health Monitoring function implemented in the Operating System Layer.

Fault Recovery services are employed when a failure cannot be masked out at a lower level. Their task is to restore the system operating capability on the basis of the recovery mechanisms specified in the blueprints. Firstly, the blueprint-based information on the recovery mechanism is retrieved from the Management Information Base: this might define a graceful degradation mechanism in order to ensure the retention of flight-critical and mission-critical functions. The reconfiguration mechanism may be static or dynamic. The specified reconfiguration itself is then performed, and all relevant elements, including logging and maintenance systems, informed accordingly.

Demonstration

Taking as an example the two applications application_1 and application_2. Initially, application_1 is the active application, and application_2 a hot stand-by implementation. In the case of a recovery from a functional application failure of application_1, the sequence of actions performed during reconfiguration might be as follows:

- Deactivate the failed application, application_1
- Activate the hot-standby application, application_2
- Inform system partners of application_2 reconfiguration
- Perform logging.

This reconfiguration process has been implemented in the blueprints as shown in Fig. 18.

```
begin_reconfig
    item := application_1;
    item_status := active;
    failure_class := application;
    failure := crash;
    begin_step
        step_number := 1;
        reconfig_action := deactivate_current_item;
        reconfig_class := application;
        reconfig_item := application_1;
    end_step
    begin_step
        step_number := 2;
        reconfig_action := activate_hot_stand_by;
        reconfig_class := application;
        reconfig_item := application_2;
    end_step
    begin_step
        step_number := 3;
        reconfig_action := actualize_partner_config_info;
        reconfig_class := application;
        reconfig_item := application_2;
    end_step
end_reconfig
```

Fig 18: Reconfiguration Aspects in Blueprints

Fig. 19 illustrates another example of a reconfiguration process. It shows a failure of an underlying physical communication channel during virtual inter-process communication.

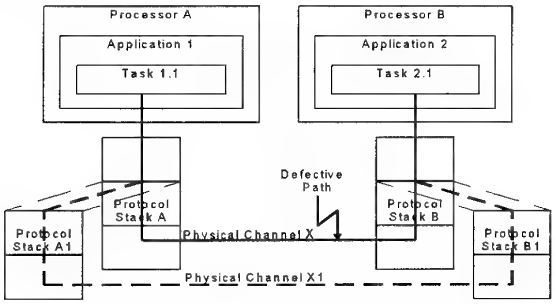


Fig. 19: Reconfiguration Example

Following reconfiguration, whereas the mapping of the virtual channel onto the physical channel has been altered, from the logical point of view the inter-process communication between Task 1.1 and Task 2.1 remains unaffected. Thus, the virtual communication channel will remain unchanged.

The design of much of the software system is affected by the fault management system:

- During reconfiguration, almost the complete software system, including both the operating system and applications, is involved.
- The fault management strategy is closely interrelated with the system management for resource allocation and scheduling during initialisation and during mode-changing at run-time.
- There is a high level of interdependency with the communication system, in that a well designed communication system and multi-cast service are essential for the fault and configuration management processes.

It is noted that during the design phase it will be a task of considerable scope and importance to identify the possible failures and their corrective actions, in order to supply information for the blueprints which will guarantee a stable and reliable avionic system under real-time conditions.

4. FUNCTIONAL APPLICATION DEMONSTRATION

The communication network and software architecture components developed as described above will be integrated into the IMA Demonstrator, and the communication and fault management capability of the IMA Demonstrator demonstrated. This will include the demonstration of representative functional applications, in order to show that the proposed IMA concepts will support applications typical of future avionic systems.

The avionics application chosen for this purpose is a flight guidance application, which results in the production of a two-dimensional primary flight display and a three-dimensional terrain grid display on a cockpit monitor. It relies on the IMA Demonstrator for variable data bandwidth transfer, real-time process execution and inter-process communication, to provide its full functionality and performance. The application will be demonstrated in a dynamic mission scenario generated by an aircraft simulation environment.

The general view of the IMA architecture for the functional application demonstration is as shown in Fig. 5, and the functional layout is shown in Fig. 20.

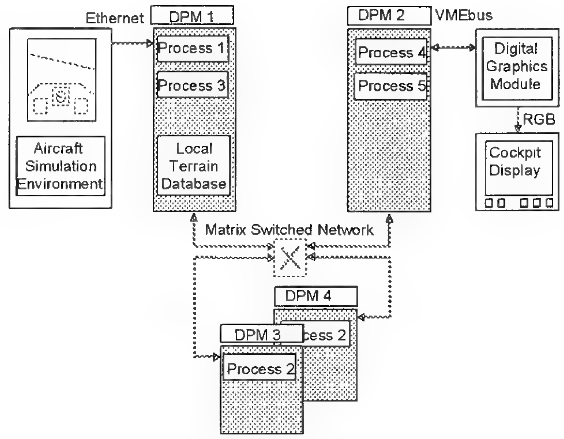


Fig. 20: Functional Applications Demonstration

The application will be split up into five processes to allow a distributed implementation on a number of DPMs. Dynamic environmental data is derived from an aircraft simulator system and transferred to an interface process (not shown) on the first DPM via an Ethernet test interface. The basic rendering will be performed by a Digital Graphics Module (DGM), which is connected to a second DPM via an interface process and the backplane VMEbus.

The five application processes execute in real-time, and may be located on and execute on any of the system's DPMs. The data transfer required between the processes covers various bandwidths: aircraft data will be transferred at a high transmission rate via small data messages, whereas terrain data transfer is event-driven and comprises large data messages. Real-time performance of all the processes is necessary to maintain a high display update rate in order to reflect the current simulated aircraft position and attitude.

The application processes will use the communication services of the operating system in order to exchange their data, allowing them to operate independently of the particular media and routing determined by the operating system and lower layers. In order to demonstrate the reconfiguration and fault-tolerance capabilities of the IMA architecture, one of the application processes will be instanciated twice, firstly as a primary executing process, and secondly as hot-standby process on another DPM. During execution, the DPM which hosts the primary executing process will be switched off and the hot-standby process on the other DPM will take over as a backup, without any effect on the application's functionality or performance.

5. CONCLUSION

With the construction of the IMA Demonstrator, a demonstration environment has been created for continuing IMA activities. In the activities addressed in this paper, key IMA concepts for the communication network and the software architecture have been refined and validated.

For the future, it is intended to build on the IMA Demonstrator to further develop the concepts for the key areas, and a number of developments would be suitable for consideration. For the software architecture, the implementation of the software concept and its operating system would be extended. Future development of the communication network would include the development of the Logical Link Control protocol, the investigation of higher-level protocols and the definition of the Network Independent Interface, and eventually the application of an optical switch matrix.

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7. ABBREVIATIONS

AMT	Analyse, Monitor, Test
APOS	Application to Operating System (interface)
ASAAC	Allied Standard Avionics Architecture Council
ATM	Asynchronous Transfer Mode
CEPA	Common European Priority Area
CMN	Control and Message Network
COTS	Commercial Off-The Shelf
DGM	Digital Graphics Module
DPM	Data Processing Module
DTN	Data Transmission Network
EUCLID	European Co-operation for the Long Term in Defence
FDDI	Fibre Distributed Data Interface
GOA	Generic Open Architecture
IMA	Integrated Modular Avionics
ISO	International Organisation for Standardisation
LCE	Link Control Element
LLC	Logical Link Control
MIB	Management Information Base
MOS	Module to Operating System (interface)
MSL	Module Support Layer
MSN	Matrix Switched Network
NII	Network-Independent Interface
NIU	Network Interface Unit
OSE	Open Systems Environment
OSI	Open Systems Interface
OSL	Operating System Layer
PCI	Peripheral Component Interconnect
POSIX	Portable Operating System Interface
RTP	Research and Technology Project
SAE	Society of Automotive Engineers
SCI	Scalable Coherent Interface
TCP/IP	Transmission Control Protocol / Internet Protocol
VME	Versa-Module Europe
XTP	Express Transfer Protocol

EXPERIMENTAL ANALYSIS OF EFFECTS OF ANOMALIES IN STRUCTURE OF RADOMES ON RADOME'S PERFORMANCE

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Abstract
In this study, radome structures, located in the nose section of aircrafts, which protect radar antennas from adverse environmental effects, fit to aircraft structures aerodynamically but which differ from other parts of aircrafts in terms of electrical features have been examined basically. Effects of radome structural anomalies to radome electrical performance have been investigated by bonding mica plates at some parts of electromagnetic window section of an F-4 nose radome which differ the thickness of the structure. Transmission loss, boresight error, boresight error measurements, have been achieved via B-350A Test Utility System. Consequently, experimental analysis of anomalies which occur as variation at density and thickness of radome structures have been evaluated.

1.Introduction

Protective dielectric structure which is called as "radardome" or shortly "radome" is used for protection of microwave or milimetric wave antennas from adverse environmental effects (1). Operation frequency range of radome is approximately between 1 GHz and 1000 GHz. Radomes are generally manufactured from low loss dielectric material whose thickness is proportional to the wavelength of the antenna covered and designed according to aerodynamical characteristics of plane of use.

2.Radome Structures

Aircraft nose radomes are classified as :
A) Single layer (monolithic)
B) A-Sandwich
C) B-Sandwich
D) C-Sandwich
E) Multiple layer sandwich
F) Dielectric layers with metal inclusions
according to their structures (2).(Figure.1.)

Monolithic layer consists of a single slab of homogeneous dielectric material. Materials for this type have included fiberglass-reinforced plastics, ceramics, elastomers and monolithic foam. The optimum thickness for a single layer is a multiple of a half wavelength in the dielectric material at the appropriate incidence angle, but many single layer radomes are simply thinwall approximations to the zero thickness case.

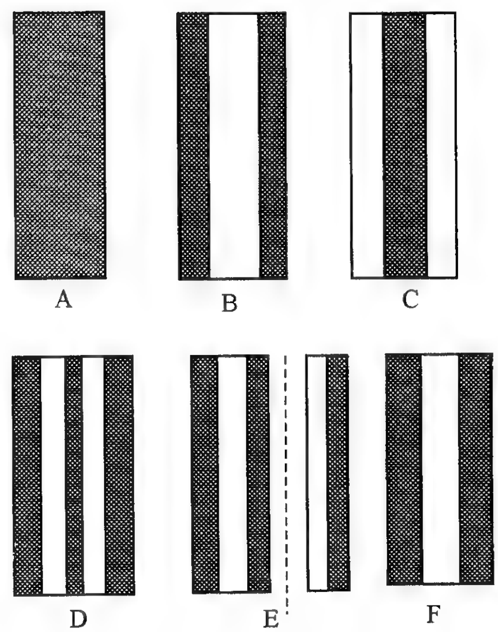

Figure.1.: Radome Structures

A commonly used radome wall cross section is the A-sandwich which consists of two relatively dense thin skins and a thicker low density core. The skins are generally fiberglass reinforced plastics and the core is a foam or honeycomb. This configuration exhibits high strength-to-weight ratios. As a rule, the skins of the sandwich are made symmetrical or of equal thickness to allow midband cancellation of reflection. It gives perfect electrical performance below 6 GHz. It allows cancellation of side band reflections.
B- sandwich is a three layer configuration whose skins have a dielectric constant lower than that of a core material. This structure is not commonly used.
The C-sandwich is a five-layer design consisting of outer skins, a center skin and two intermediate cores. The symmetrical C-sandwich can be thought of as two back-to-back A sandwiches. This configuration is used when the ordinary A sandwich will not provide sufficient strength, or for certain electrical performance characteristics.
Multiple layer sandwiches of 7, 9, 11 or more layers are sometimes considered when great strength,

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good electrical performance relatively light weight are required. Some of these designs have used thin layers of fiberglass laminates and low density cores to attain high transmission performance over large frequency bands.

Metal inclusions have been considered for use with dielectric layers to achieve frequency filtering, broad-frequency-band performance, or reduced-thickness radomes. Thin layers of metal inclusions exhibit the characteristics of lumped circuit elements shunted across a transmission line. For example, a grid of parallel metal wires exhibits the properties shunt-inductive susceptance.

Nose radome of an F-4E aircraft which has been used in this study has a structural design called as "filament-wound" (3). It is a single layer type. Layers consisting of fiberglass are wrapped perpendicular around each other in accordance with the conical shape of radome and bonded with resin. Then thermal curing operation is applied to this structure. The shape of radome is "tangent ogive" which fits to aircraft structure aerodinamically (Figure.2).

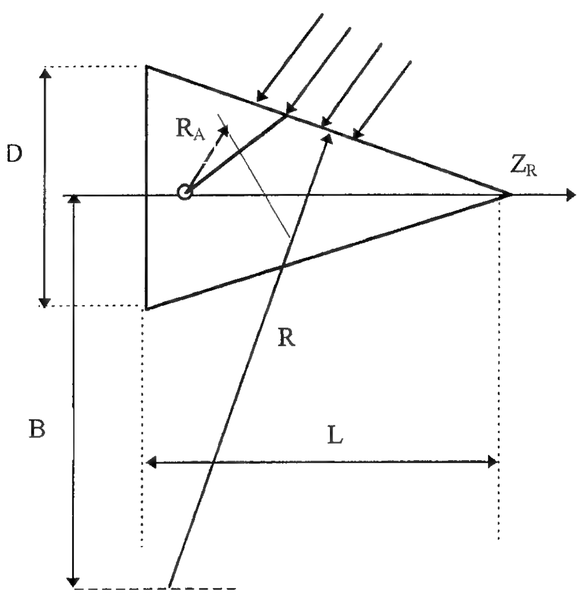


Figure.2.: Antenna-Radomes Geometry

Electrical characteristics of filament wound radomes and other wall structure types are given in Table-1. These characteristics are function of density and resin compositions(4).

Table.1.: Electrical characteristics of radome wall structures

Type	ε_r	Loss Tang.
Polyester-glass	3.6-5	0.01-0.02
Epoxy-glass	3.6-5	0.01-0.02
Fused slica	3.4	0.008
Alumina	9	0.003

Radome wall structures combine material technology and electrical characteristics of plane layer. Single layer wall structure consists of single layer dielectric material and its thickness is less than 1/10 λ. For adequate strength at higher frequencies, the monolithic wall thickness is chosen according to ;

$$d = \frac{n\lambda}{2\,(\varepsilon_r - \sin^2\theta)^{1/2}} \qquad (1)$$

Where n is an integer with a value of "1" for λ/2 wall. λ is wavelength of free space, ε_r is relative dielectric constant and θ is incidence angle. "θ" is also called as "design angle". Reflection is zero at this angle for perpendicular and circular polarization. Maximum and equal transmittance will be obtained and equal insertion phase delays will be introduced by the plane dielectric sheet. (3)(figure 3).

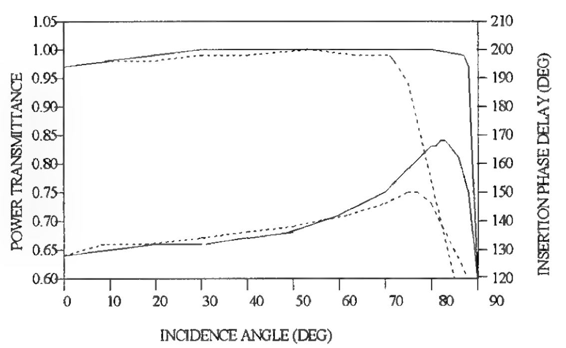
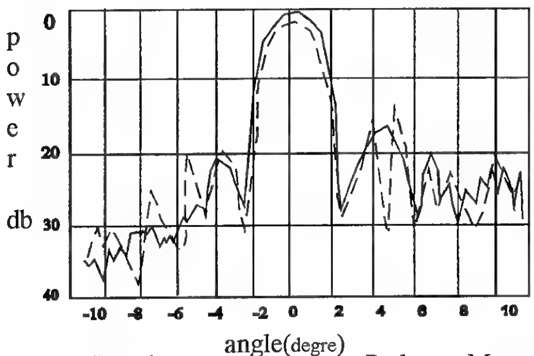


Figure.3.: Power transmittance (upper curves) and insertion phase delay versus incidence angle for alümina half-wave panel having a design angle of 55° for parallel (solid curves) and perpendicular dash) polarizations (ε_r=9.3, tan δ =0.0003,d=0.17λ)

A radome always changes the electrical performance of the antenna because of wave reflections and refractions at interfaces between material media and because of losses in the radome materials.These changes manifest themselves as :



——No radomes , ------Radomes Measure.

Figure.4.: Effects Of Distortion In Antenna Diagram

Pattern distortion including changes in gain, sidelobe levels, beam width, null depth and polarization characteristics(Figure.4). Excessive reflections from the radome may cause magnetron pulling. For high-power applications, excessive losses in the radome material may raise its temperature· to a point at which its structural properties and electrical performance are degraded. Radome losses also will raise the system noise temperature. Radome effects can be qualitatively explained and understood in terms of TEM (plane) wave propagation through and reflection from planer dielectric each point. Waves emanating from the enclosed transmitting antenna are also considered to be locally plane at each point of incidence on the radome wall. The reflected and transmitted waves can then be approximated from plane-sheet theory.

The transmission properties of a plane dielectric sheet vary with frequency, incidence angle, and polarization of the incident plane wave. (Figure.5)

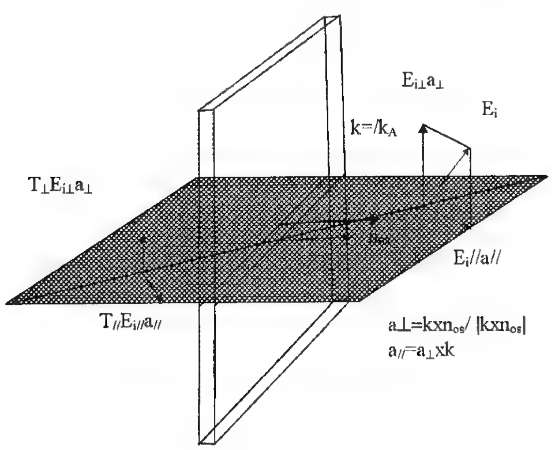


Figure.5.:Plane-wave propagation through a flat dielectric panel

The plane of incidence is defined by unit normal (n_{os}) and the direction of wave propagation ($\vec{k}$). The incidence angle is given by $\sin^{-1}(k \times n_{os})$.

Arbitrary wave polarizations are resolved into an electric field component perpendicular to the plane of incidence($E_{i\perp}$). The power transmission coefficient (transmittance) and insertion phase delay (IPD) are generally different for the two polarizations. The electrical characteristics of flat planes are important because radome-wall design is based on them.

3.Effect Of Radomes On Antenna Performance

Radomes affect antenna performance as follows while they are protecting antenna from adverse environmental effects.

1.Beam Deflection: It is shifting of electrical axis and is a critical effect for seaker radars.

2.Transmission Loss: It is the measured loss of energy caused by reflection or absorption of incoming beam to the radome.

3.Reflected Power: It causes mismatching of antennas at small radomes and sidelobes at pattern graphics at large radomes.

4.Secondary Effects: It disturbs planar polarization and causes antenna noise.

These four main electrical effects cause following malfunctions because of its direct effect on radar performance during target seaking, finding, locking and firing phases of an aircraft.

Transmission Efficiency Loss: Transmission efficiency loss is the ratio of power of outgoing radar beam from radome wall to power of incoming radar beam to radome wall and it is given as percents.

$$\alpha_{transmission} = \frac{P_{out}}{P_{in}} \qquad (2)$$

Where ;

P_{out} : Power of outgoing radar beam from radome wall

P_{in} : Power of incoming radar beam to radom wall.

$\alpha_{transmission}$: Transmission efficiency loss

Existance of radome infront of antenna causes transmission efficiency loss and it decreases the range of wave. This decreases effective sense range of aircraft radar.

Effects Of Boresight Error :

Boresight error is defined as the difference between actual sight angle and fictitious sight angle of an object. An electromagnetic wave being transmitted through a media can be subject to reflections and refractions through another media.

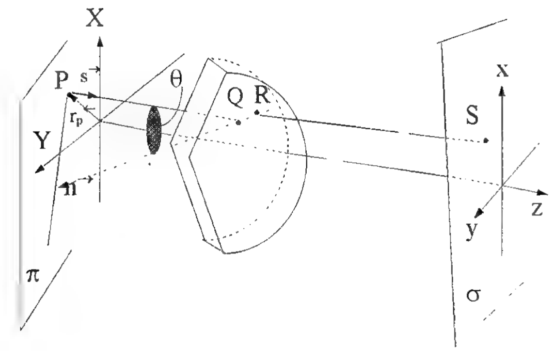
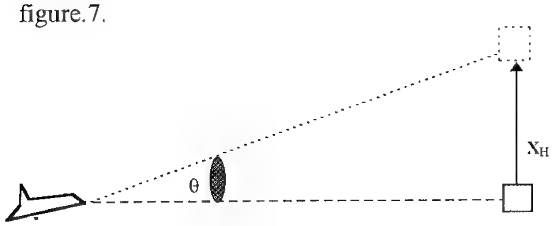


Figure.6.: Diffusion electromagnetic wave from radome material.

If the electromagnetic wave comes to the observer eye with second media angle (as it is seen from Figure 6) the observer sees the wave with that angle and boresight error occurs. Boresight error is defined by the following formula :

G_H=A seen - A actual (3)

Where :
G_H : Boresight error
Aactual: Actual sight angle of object
A_{seen} : Angle through which the object is seen
Boresight error is an angular value and its unit is "radian".But since radian is excessive for boresight miliradian (mR) is used instead. Position of the target is determined by radar antenna by means of sending the wave to the target and sensing the reflected wave from target. If the boresight error exceeds the limits (4 mR) the error affects the operation negatively. This situation is shown in figure.7.



Firing distance: L

Figure.7.: Formation of boresight error

From Figure-7 ;

$$\tan\theta = \frac{X_H}{L} \quad (4)$$

By utilizing above formula boresight error is calculated.
In this formula.
X_H : Distance between the actual and fictituous position of target
L : Firing distance
θ : Boresight angle

Effects Of Distortion In Antenna Diagram
A three axis measurement media with a shape of lobe exists in the front, side and rear areas of the antenna in case of no obstacle in front of antenna (no radome). During radome tests, distortion rate of antenna pattern is determined by observing the size of main lobe peak point. If the reduction in size of subject peak point is in limits, this means result of the test is positive.

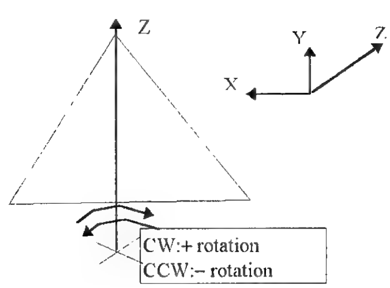
4. Experimental Analysis Of Effect Of Radome Structural Anomalies to Antenna Performance
During manufacturing of radomme wall, if the density of resin and fiberglass cannot be maintained the same at every point in the structure homogenity of the material is destroyed and thickness of the wall changes from point to point. These are called as "structural anomalies" of radome.

4.1. Experimental Study
In this experimental study, an artificial anomaly has been introduced to the radome and boresight error measurement has been achieved. Then this anomaly has been removed and boresight error has been measured again. Consequently difference between both error values has been calculated and interpreted.
During the experiment a "mica plate" with size of 10cmX10cm and with a thickness of 2 mm has been used in order to set up the anomaly. (ε_r= 6).

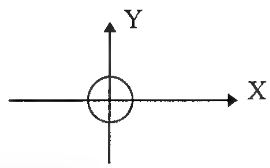
Measurement System, Antenna and Test Equipment Used In The Experiment
Antenna and radome used in the measurements have been located in the same position used in the aircraft. Equipments used in the measurements are listed below;

AN/APQ-120 Test Antenna
CARCO MODEL B-350A-TU System
HP-8757C Network Analyzer
HP-11664A Detector
HP-438A Powermeter
HP-8484A Detector
HP-8473D Detector
Mechanical Adapters
Other auxilliary equipment

Experimental Geometry:



Null Seeker:



Geometrical position of the null seeker on which the transciever is located moves in X and Y axis.

Two movement has been given to radome. These are;
1. 45 degree roll angles in CW direction -45 and -90 degrees roll angles in CCW direction have been given to Z axis which is called ROLL axis.
2. (0) - (-60) degrees azimuth traverse has been achieved in x axis. (movement of radome parallel to the ground).
3. Frequency : 8.795 GHz
4. Power : Approximately 0.260 μW

EXPERIMENT 1

Boresight error and transmission effectiveness measurements have been achieved and their graphs have been obtained using radome without anomalies. Then, boresight error according to block diagram given in figure.10 and transmission effectiveness according to figure.9 measurements have been achieved using radome with anomalies. (figure.8.)

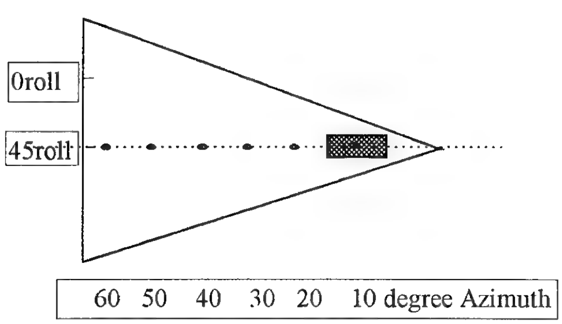


Figure.8.: Position of the anomalies on the radome

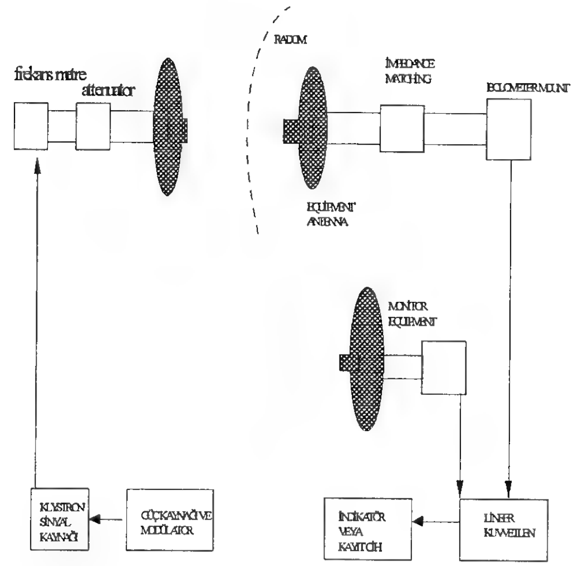


Figure.9.: Transmission test block diagram

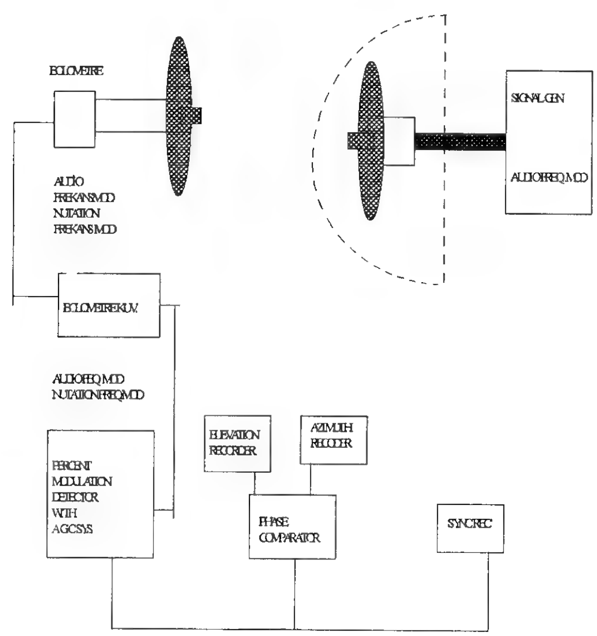


Figure.10.: Boresight error measurement block diagram

In the first experiment anomaly plate has been attached to the radome with a roll angle of 45° and an azimuth angle of 0° to 12°. Boresight error measurement results have been compared and a difference graph has been obtained (figure 11).

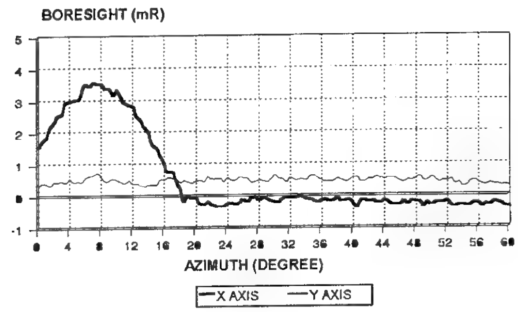


Figure.11.: Boresight error difference graph

It is seen from the above graph that anomaly produces maximum 3.5 mR boresight error through X axis between 0° to 18° azimuth angle range. Between 18° to 60° azimuth azimuth angle range, there is no significant change. Through Y axis, since normal and anomaly graph characteristics remain nearly same no excessive peak points are observed. Maximum difference occurs at 8° azimuth angle which corresponds to max 0.8 mR.

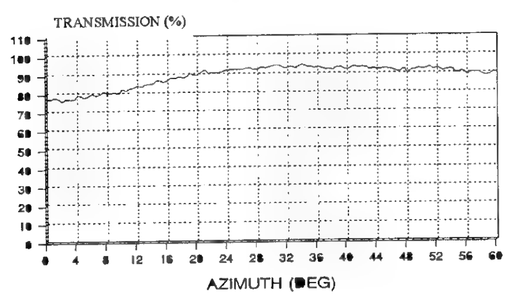


Figure.12.: Transmission measurement with anomaly

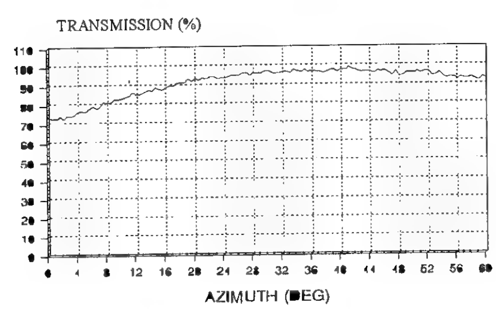


Figure.13.: Normal transmission measurement

If transmission effectiveness measurement graphs with anomaly and without anomaly (Figure 12 and 13) are investigated, it is seen that there is an average reduction of 6% at transmission effectiveness through whole area inspite of the fact that anomaly plate has been located between 0°- 18°.

As a result, it has been determined that the anomaly plate located between 0°-18° azimuth angle at 45° roll angle of radome affects the boresight error excessively, besides it causes a reduction at transmission effectiveness.

EXPERIMENT 2

In this experiment anomaly plate has been attached between 20° to 32° azimuth angle at -45° radome roll angle (Figure 14). Boresight error and transmission effectiveness measurements have been achieved with anomaly and without anomaly and relevant graphs have been drawn.

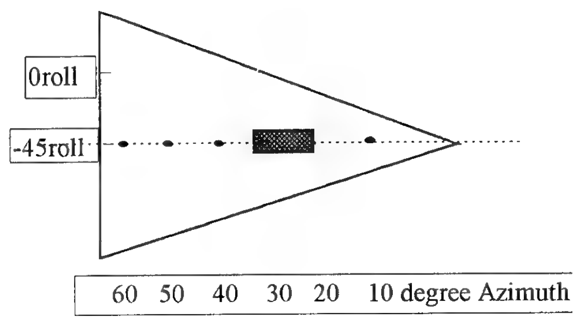


Figure.14.: Position of anomaly on radome

If boresight error difference graph (Figure 15) is investigated, it can be seen that -2.8 mR at 15° azimuth angle and 3.15 mR at 42° azimuth angle boresight error difference values through X axis have been obtained. There is no significant change through Y axis.

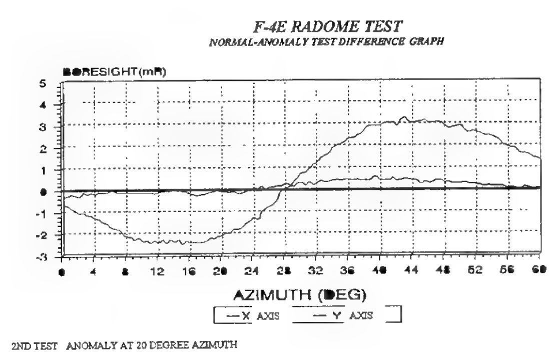


Figure.15.:Boresight error difference graph

If transmission effectiveness measurement graphs with anomaly (figure.17) and without anomaly (figure.16) are investigated, it is seen that anomaly produces an average reduction of 5% through whole azimuth range.

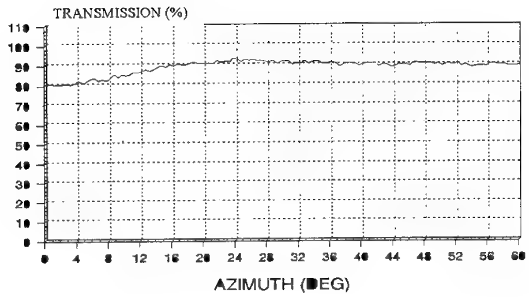


Figure.16.: Graphs without anomaly

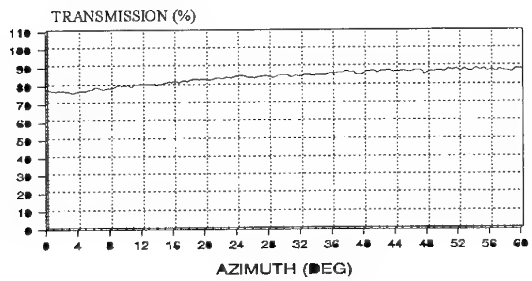


Figure.17.: Graphs with anomaly

As a result, it has been determined that the anomaly plate located between 20° to 32° azimuth angle at -45° radome roll angle affects the boresight error excessively, besides it causes a reduction at transmission effectiveness.

EXPERIMENT 3

In this experiment anomaly plate has been attached between 30° to 42° azimuth angle at 90° radome roll angle (figure 18)

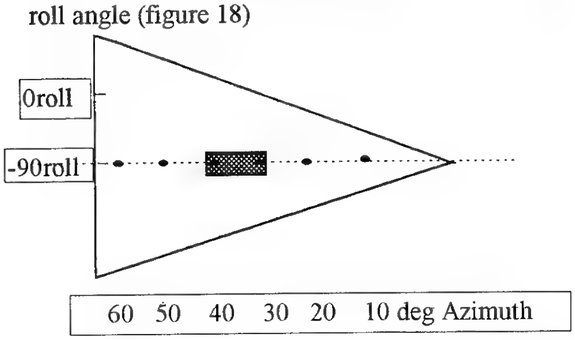


Figure.18.: Position of anomaly on radome

Since previous experiments have revealed that major effect of anomaly plate is on boresight error rather than transmission effectiveness only boresight error measurements have been achieved in this experiment.

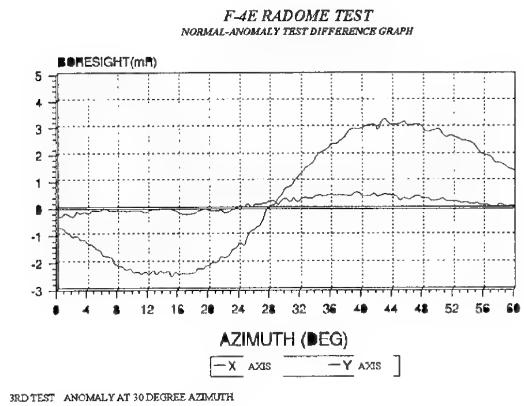


Figure.19.: Difference graph

If boresight error difference graph (figure 19) is investigated, it can be seen that maximum value of boresight error difference through X axis has been obtained as 3.2 mR at 56° azimuth angle. There is no significant change through Y axis. This experiment has revealed that anomaly plate located between 30° to 42° azimuth angle at 90° radome roll angle affects the boresight error excessively.

CONCLUSIONS

Ideal radome structures are transparent electromagnetically. Besides ideal radome materials react to all wavelengths the same as they react to free space wavelength electromagnetically. Radomes are subject to critical aerodynamic load, temperature, rain and wind errosion. During design of a radome an optimization should be done in order to meet the mechanical requirements as well as the electromagnetic requirements. High density materials, such as alumina and ceramics are used for heat resistance. Radome anomalies caused by density and thickness variations in the radome structure affect the electromagnetic transparancy. Besides they affect the performance of the antenna located in radome. In order to observe these effects in details artificial anomalies have been introduced to the radome of an F-4E a/c and transmission and boresight error measurement graphs have been drawn. The analysis of these graphs revealed that radome transmission effectiveness reduces at anomaly area. This decreases the sensing capability of the a/c which means sensing range decreases. Another negative effect is the increase at boresight error. This means the a/c senses the target shifted from its actual location. This is a vital effect which decreases the shooting capabiliy of the aircraft.

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CAPRICORNIO Launcher: an Approach to a Modular and Low Cost Software Architectural Design

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1 SUMMARY

This paper introduces the Capricornio Programme by means of describing the vehicle requirements, architecture and guidance philosophy as well as the required ground facilities. Later and in a more detailed way, Requirements Specifications and Top-Level Design of CAPRICORNIO Launcher Software are presented, with a reference to the static and dynamic behaviour of the chosen architecture. Hardware interaction aspects are omitted. Regarding the Ground Control Computer Software, an overview of the Rapid Prototyping Technique through LabVIEW® is presented with a look to the first results. This article shows how a low cost software is being developed with a high modularity and flexibility degree allowing an easy migration among demonstrator vehicles (ARGO) and finally, the CAPRICORNIO launcher.

2 LIST OF SYMBOLS AND ACRONYMS

t	time
θ	pitch angle
ψ	yaw angle
X'	horizontal speed within the trajectory plane
Z	vertical coordinate
Z'	vertical speed

ARTK	Alsys® Real-Time Kernel
BIT	Built-In Test
CCM	Communication Control Module
GCC	Ground Control Computer
I/O	Input/Output
INS	Inertial Navigation System
INTA	Instituto Nacional de Técnica Aeroespacial
MPCC	Multi-Protocol Communication Controller
OBC	On-Board Computer
TC	Telecommand
TM	Telemetry
TVA	Thrust Vector Actuator
TVC	Thrust Vector Control

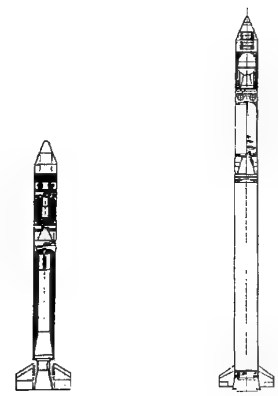

Figure 1: ARGO and CAPRICORNIO vehicles

3 INTRODUCTION

After a remarkable experience in the field of weapon and sounding rocket [1] [2], in 1989, INTA began studies on the feasibility of a Spanish micro-satellite launcher: the CAPRICORNIO vehicle [3].

The objective of the Capricornio Programme is the development of a launch vehicle capable of injecting micro-satellites (up to 100 kg) into a low orbit (600 km). In addition to this objective, the programme aims to promote the capability of INTA and Spanish industry in both the design and integration of this kind of vehicles, as well as in the technologies involved. The vehicle will consist of three solid propellant stages, with a total mass of 15 tons and an 18 m length.

Basic requirements for the vehicle were divided in two classes [4]:

Primary:
- satellites weight: 50-100 kg
- orbit: 600 km, circular
- launching point: Spanish territory (Huelva coast or Canary Islands)

Secondary:
- postdeveloping possibilities
- as high national participation as possible.

Paper presented at the AGARD MSP Symposium on "Advanced Architectures for Aerospace Mission Systems", held in Istanbul, Turkey, 14-17 October 1996, and published in CP-581.

The vehicle was called Capricornio (**Figure 1**) and its configuration was established as follows:
- Total weight: 15000 kg
- Total length: 18 m

1st stage:
- motor: CASTOR IVB (Thiokol corporation)
- TVC (Thrust Vector Control)
- aerodynamic controls to limit roll rate

2nd stage:
- motor: DENEB (new development)
- TVC (pitch and yaw)
- cold gas thrusters (roll)

3rd stage:
- motor: MIZAR (new development)
- cold gas thrusters (pitch, yaw and roll)

Prior to Capricornio development, INTA began in 1993 the development of ARGO, whose first prototype will fly late 1996, a demonstrative vehicle to develop and test DENEB and MIZAR motors and as many Capricornio components as possible. ARGO configuration is as follows:
- Total weight: 3900 kg
- Total length: 9 m

1st stage:
- motor: DENEB (without TVC)
- aerodynamic controls (roll)

2nd stage:
- motor: MIZAR
- TVC (pitch and yaw)
- cold gas thrusters (roll)

Guidance Philosophy

The guidance algorithm is conceived as an attitude guidance where the vehicle is requested to follow a pre-programmed nominal (plane) trajectory. The objective is to reach the proper attitude and velocity at the apogee. Guidance is only possible during those stages where TVC is present. Provided these rocket motors have no means to cut combustion, accuracy is greatly affected by external disturbances and the exactness of the rocket motor model related to thrust and combustion time.

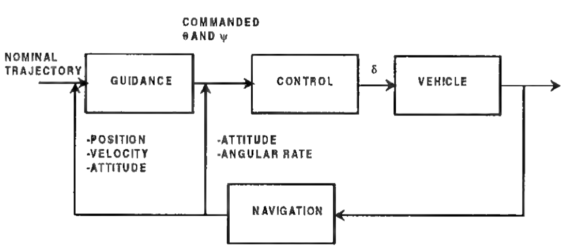

Figure 2: Guidance, Navigation and Control

As the characteristic frequency of TVC is 5 Hz, control frequency has been fixed on 25 Hz. Functions performed every computation cycle are (**Figure 2**):

* get t, θ, Z, X' and Z', both current and nominal. Nominal data are stored with an interval of 1 second. An interpolation between two consecutive records is necessary (**Figure 3**). Current data (navigation) are to be supplied by a strapdown INS (Inertial Navigation System).

* calculate commanded θ and ψ as linear functions of the deviations of the former trajectory parameters (guidance).

* calculate nozzle deflections by implementing a proportional/derivative control, as linear functions of the deviations between current and commanded angles and rates.

t	θ	Z	X'	Z'
.01	.339664	26563.780	399.164	1128.928
1.01	.342213	27685.590	397.656	1115.042
2.01	.343804	28815.690	411.949	1145.415
3.01	.344376	29976.950	426.851	1177.370
4.01	.344580	31170.950	442.326	1210.880
5.01	.344651	32399.230	458.355	1245.921
6.01	.344676	33663.300	474.931	1282.484
7.01	.344685	34964.680	492.045	1320.551
8.01	.344688	36304.860	509.693	1360.109
9.01	.344688	37685.360	527.870	1401.153
10.01	.344688	39107.660	546.580	1443.682
11.01	.344688	40573.240	565.822	1487.702
.	.	.	.	.
.	.	.	.	.
.	.	.	.	.

Figure 3: Nominal trajectory records

A complete system

The Programme aims to develop both the vehicles and the facilities needed to operate them. They conform the system depicted in the **Figure 4** which consists of:
- ***Ground Control Centre*** with the following functionalities:
  * Safety
  * Operation
  * Mission
  * Testing
  * Firing switching
  * TM (Telemetry) acquisition
- ***Block House*** consisting of the GCC (Ground Control Computer) and a firing system.
- ***ARGO vehicle*** in which the On-board computer and communications control boards are placed.
- ***Communication umbilicals, dedicated lines and power lines.***

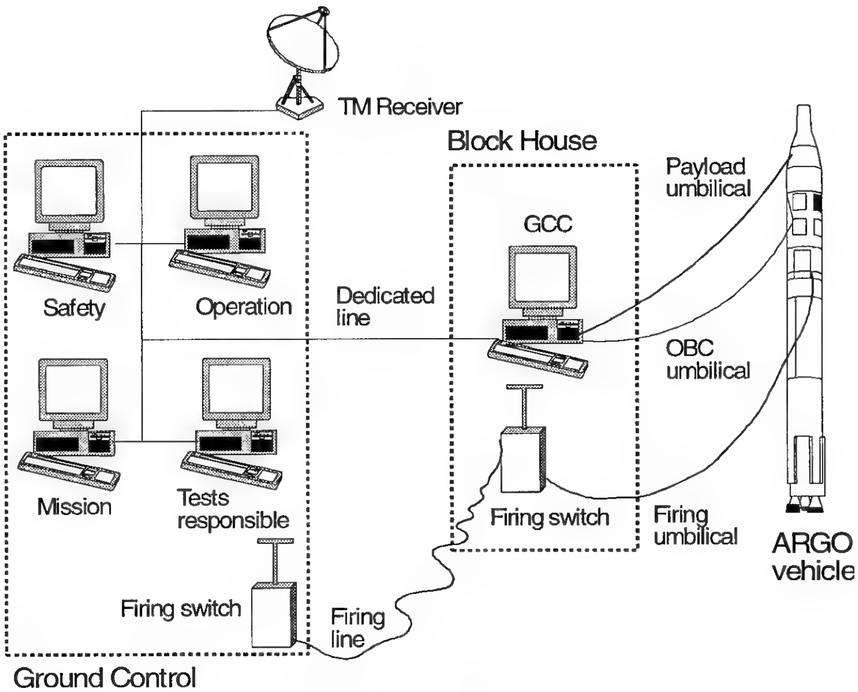

Figure 4: Launching place schema

4 AVIONICS

Avionics design uses specially developed integrated - systems with the accent on state of the art technology, a high level of integration, flexibility and adaptability to the various mission requirements, minimum mass and low cost of test and launch support.

The main element is the OBC (On-board Computer, **Figure 5**). It consists of two boards, CPU-40 and MPCC-1 (Multiprotocol Communication Controller), linked by a VME bus. Specific boards are PMV 68 CPU-40 and PMV 68 MPCC-1, both Military Conduction Cooled model, from Radstone Technology® PLC, based on Motorola® 68040 and 68020 respectively.

CPU-40 is the main processor unit, with a 25 Mhz 32 bits processor, two RS-423 channels and a SRAM, FLASH and EEPROM memory configuration that makes 'In System Programming' feasible, for mission specific parameters.

MPCC-1 is devoted to managing communications within the vehicle, discharging CPU-40 of these tasks. It provides 4 RS-422 synchronous/asynchronous (configurable) full duplex channels, and is able to transmit up to 500 Kbits/s in all four channels simultaneously.

One of the channels links the INS, reading HDLC data frames at 100 Hz, with a rate of 460.8 Kbits/s. INS model is SAGEM AGYLE SP-10.

Another channel links the telemetry transmitter (TM). This is the most stressed link, as it has the larger amount of data, sum of the remaining links.

The last used channel (4th one is spare) connects all vehicle actuators and transducers through a multipoint line. Each secondary station consists of a CCM (Communication Control Module), an INTA Avionics Department development based on a Motorola® 68302, which includes both processor and communication control, mounted over a single-Europe size board configuring a multi-purpose communication and data acquisition computer to which another single-Europe size board with the required analog and digital I/O (Input/Output) is plugged.

There are several CCMs along the vehicle, each one dealing with several actuators and transducers. For example, ARGO CCM-1 is in charge of distributing commands to the ailerons and collecting several different data: aileron position, aileron temperature, DENEB chamber pressure and nozzle temperature.

There are only two commands which are not processed by OBC: 1st stage firing, which is wired to a switch box within the Block-House, and the destruction system, which is telecommanded from the

ground facility. Additionally, high sampling frequency data are not processed by OBC but directly packed and sent with the remaining telemetry data.

Communications along the vehicle are HDLC coded giving high reliable links and allowing an easy connection to current computer networks. This is a useful feature, specially during development. The multipoint vehicle data line uses, as stated above, an RS-422 interface. This configuration allows each CCM to be individually connected to a COM port of a standard PC and be checked out with a dedicated software prior to integration.

On-board communication timing is based on a 100 Hz signal provided by the INS directly to the CPU-40 board which produces the 25 Hz communication signal that synchronizes CCMs to sample and transmit data.

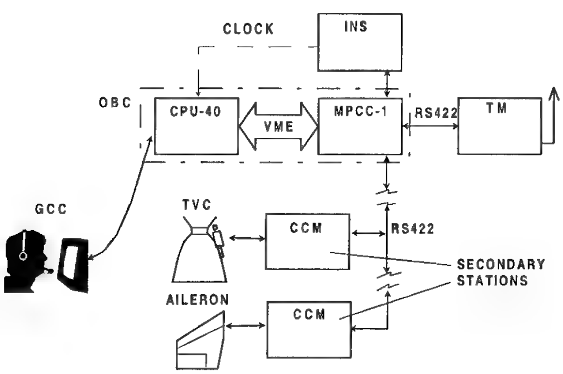

Figure 5: Avionics Architecture

5 SW DEVELOPMENT METHODOLOGY

Characteristics of the avionics software programs

The on-board computers are the cornerstone of the avionics systems whose development spans nearly a decade. The avionics software offers the following main characteristics:

- an **incremental development**: it is indeed impossible to wait until the definition of the entire system is completed to initiate the software development.

- a **capability to implement evolutions**: the development and generation of avionics system and their associated components, give rise to requests for changes concerning the software specifications. Throughout the launcher operational life, corrective and upgrading maintenance must be affordable within very short time periods.

- **very demanding technical requirements** (***real-time constraints***): the avionics software programs are subjected to stringent real-time requirements (reaction time imposed amounting to a few milliseconds) and also severe quality requirements (dependability, efficiency, sturdiness, safety, reliability,...)

- **economic efficiency**: the open-endedness and reusability of software components have become critical criteria for the development of avionics software programs. In addition, the rapid evolution of hardware technologies has led to the emergence of a portability requirement designed to make the software programs as independent as possible from the processors and the computer architecture.

Software development methodology

For the development of all the software in the CAPRICORNIO programme, INTA's own methodology has been chosen. This methodology is based on the European Space Agency software development standards.

Initially, a simple "*V*" software life cycle was envisaged, but the experimental and volatile nature of some requirements made us change to an ***incremental development*** life cycle (**Figure 6**). Each step of the incremental model contains significant variations with regard to the previous one on the mission characteristics: number of stages, stages attributes (such as duration, events detected, actions to be performed, actuators to be controlled,...) payloads, apogee, etc. The software design should allow an easy adaptation to the next increment with the minimum effort. In order to achieve this target, the architecture shall have a high degree of modularity.

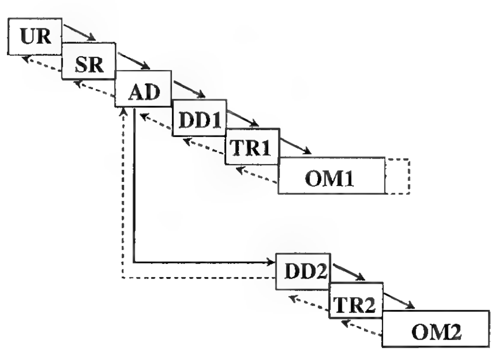

Figure 6: Incremental delivery approach

For the GCC software a *rapid prototyping* approach was selected in order to froze the user interface requirements as soon as possible. The prototype layout is depicted in **Figure 13**.

The Software Requirements phase

In the ***Software Requirements*** definition phase, the developers construct an implementation independent model of what is requested by the users. This model is called ***logical model*** and represents the functional decomposition of the system. To build the logical model, a ***Yourdon-DeMarco Structured Analysis*** with a real-time extension approach has been used: ***Ward & Mellor*** [6]

In the ***Ward & Mellor*** approach, the model consists of two parts: a model which focuses on defining what the system must interact with, and a model which describes the required behaviour of the system. Both models are implementation free.

- The ***Environmental*** model is a description of the environment in which the system operates. This model has two pieces:
  - the ***Context Diagram*** which describes the boundary that separates the system from the environment.
  - the ***Events List*** that occur in the environment to which the system must respond.
- The ***Behavioural*** model is a description of the required behaviour of the system. This model has also two pieces:
  - the ***Transformation Schema***: graphic representation of the processes.
  - the ***Data Schema*** to define the information within the system.

The Architectural Design phase

In the ***Architectural design*** phase, the developers define a collection of software components and their interfaces to establish a framework for developing the software. To construct the software architecture a formal method based on the ***Buhr*** diagramming technics has been used. The software is decomposed into a hierarchy of components according to the top-down ***Buhr*** approach.

The programming language

To implement the on-board software the *Ada* language has been selected, taking into account its modularity to define a strong software structure.

6 DEVELOPMENT ENVIRONMENT

In order to manage a complex software development, the Software Development team uses the following set of tools:

- Specification Tool: StP®
- Design Tool: Popkin® SA, LabVIEW®
- Coding: Alsys® Ada, LabVIEW® and Watcom® C
- Test: LDRA TestBed®
- Configuration Management: CVS, RCS. These tools ensure the coherence and sharing of software components.
- Simulators: Microsoft® Visual C++, Lab-Windows® libraries.

The hardware development environment is depicted in **Figure 7.** It consists of:

- *Host*: Sun® SPARCstation 20 for OBC software development.
- *PC 486* for GCC software development.
- *Development Rack* which contains:
  - * the *CPU40:* target development board,
  - * the *MPCC-1*: communications development board and
  - * the *ENET-1*: ethernet connection board.

The Real-Time System

To develop the Real-Time executive, the executive provided with the Alsys® Ada compiler will be used. This consists of a specific real-time kernel (Alsys® Real Time Kernel, ARTK) that provides low-level services that can not be expressed efficiently in Ada.

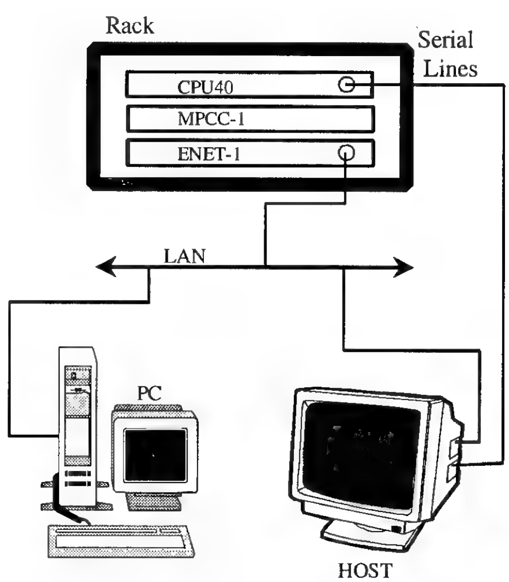

Figure 7 : Hardware development environment

7 ON-BOARD COMPUTER

On-board systems are characterised by a large number of I/O operations. A large part of the I/O processing management is implemented in the MPCC-1 board in order to avoid the main board (CPU40) overhead.

The CPU40 board is in charge of driving the vehicle throughout its operational life by means of the On-board SW subsystem.

Software Requirements definition

SE_ARGO stands for ***"Software Embarcado - ARGO"*** which means "ARGO On-board SW" and will support the following functionalities [7]:

- System monitoring using the status data provided by the sensors located in the subsystems of the vehicle. Functions available will be:
  - to initialize and check subsystems during the prelaunch phase
  - to check all the alarms during flight
- Guidance and Control: to execute the guidance routines and generate the commands to be sent to the actuators placed on each stage in order to follow the nominal trajectory and to keep the vehicle stable.

- Mission management, to execute the actions to achieve the mission objectives. These actions will be events or fault driven and will allow the configuration changes of the launcher during flight (staging, engine firing...). Therefore, they will be responsible for the software mode changes.

- I/O services. Functions available will be:
  - to provide the communication board with the ***SE_ARGO*** available telemetry which will contain *SE-ARGO status, CPU health status, guidance and control commands, mission commands, etc.*
  - data acquisition.

- Timing control services for software timing constraints.

The behaviour of the software is defined using a ***transition states diagram*** (
Figure 8) in which each transition is performed taking into account the events produced during the mission. The following states are considered:

- ***ARGO Off***: represents the state in which the vehicle is placed on the launching pad and all the equipments are ready to be powered.
- ***Mission cancelled*** could be reached if the GCC operator requires it.
- ***Initialization*** represents the state in which all the equipments will be initialized.
- ***Prelaunch checks*** to perform all the subsystem BITs (Built-in Tests) required by the GCC operator.
- During the ***Launch*** state, a sampling of the umbilicals and firing chamber pressure sensors will be performed in order to establish if the firing has been produced.
- ***1st stage flight*** in which only the roll control will be performed.
- ***Interstage flight*** state will be reached when the DENEB engine combustion is finished. First stage separation will be commanded.
- ***Pre-ignition 2nd*** stage state will be reached when the first stage separation is detected. The MIZAR engine ignition will be commanded.
- Once the ignition is detected ***2nd stage flight*** state will be reached. Roll, Pitch and Yaw control will be performed.
- ***Captive flight*** state will be reached when the MIZAR engine combustion is finished. Second stage separation will be commanded.
- ***Ogive aperture*** state will be reached when the second stage separation is detected. Pointing manoeuvres will be performed.
- ***Experimental flight*** represents the state in which the aperture has been successfully performed. Pointing manoeuvres required by the experiment will be performed.
- ***Final flight*** state will be reached when the experiment is finished.

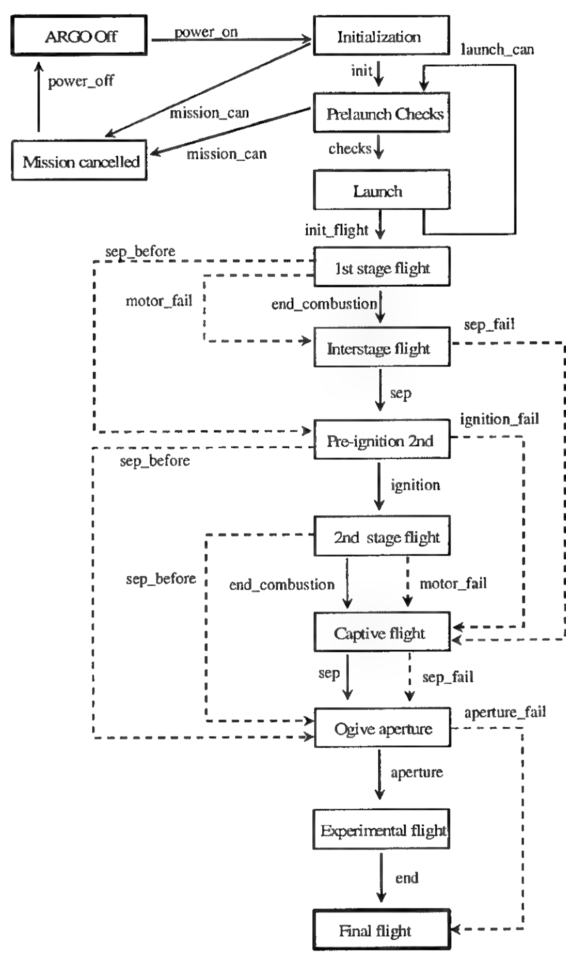

Figure 8: ARGO transition states diagram

The description of the environment in which the system operates is depicted in the Environmental model (**Figure 9**). The logical external entities identified are:

- **INS** which provides the ARGO navigation data and receives the commands needed to control its functional modes.
- **GCC** sends the commands to perform the prelaunch tasks and receives its results.
- **CLK.** The clock will drive the behaviour of the system. The basic functional cycle will be of 40 ms. Every cycle, guidance and control routines will be executed and the corresponding commands will be sent, mission actions will be commanded, check activities will be performed and the associated Telemetry will be sent to the communication board.
- **MPCC-1.** The communication board provides the status information of all the vehicle subsystems. It accepts the commands to drive the launcher and distributes it to the corresponding subsystem.

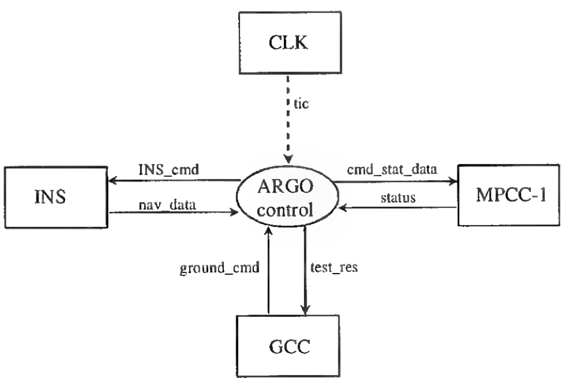

Figure 9: Environmental diagram

The *Environmental diagram* is broken down into a hierarchy of processes which conform the *Transformation Schema.* A summary of the schema is presented in **Figure 10** in which two levels are depicted.

"***ARGO control***" is broken down in five processes:

1. *Receive vehicle data,* shall obtain and prepare the vehicle status information.
2. *Generate command* is in charge of perform:
   - flight operations: send commands to drive the vehicle and to carry out the in-flight checking activities.
   - prelaunch operations: send commands to initialize subsystems and perform the on-ground checks.
3. *Build frame,* is in charge of packing the TM and TC (TeleCommand) frame.
4. *Receive ground data,* during the prelaunch activities.
5. ·*Generate cycle* is in charge of providing the timing signal for synchronisation purposes.

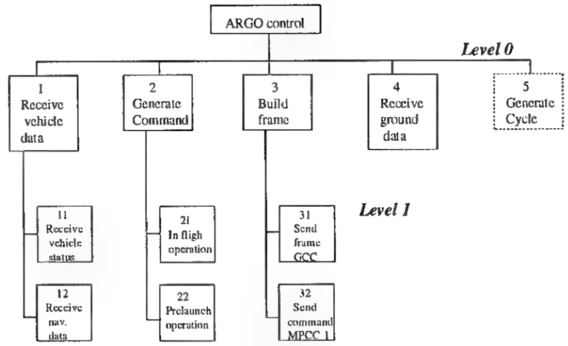

Figure 10: Break down diagram

Architectural Design

Following the results obtained during the analysis, a set of SW components were defined [8]. The top-level architecture diagram is depicted in **Figure 11.** The first level contains a set of encapsulated packages which export services or data structures represented with arrows in the diagram. These packages are subsequently described:

- ***cpu-main*** will contain the *main program,* the *scheduler* and the *watchdog* task responsible for the surveillance of the system. A cyclic executive has been chosen with a primary curl of 40 ms. duration. Taking into account the current mode, a function call sequence will be executed in order to perform the mission and guidance activities.
- the ***timing*** package, is in charge of capturing the tick interruption from the INS and provide it to the watchdog and the scheduler for tasks synchronisation.
- the ***mission*** library contains all the functions needed to generate the commands to be sent to the mission elements (such as *pyros*) in order to achieve the mission objectives. The set of functions that shall be executed once per cycle, depends on the current operational mode.
- the ***guidance*** library contains all the routines needed to generate the commands to be sent to the actuators in order to guide (following the nominal trajectory) and control the vehicle during the flight.
- the ***checks*** package consists of two sub-packages for both prelaunch and flight testing.
- the ***TC*** package contains the functions needed to pack the telecommands generated each cycle. It consists of two sub-packages for both GCC and MPCC-1 TC.
- the ***TM*** package contains the functions needed to pack the available telemetry each cycle. It consists of two sub-packages for both GCC and MPCC-1 TM.
- the ***mode change*** package is in charge of deciding the operational mode for the current computation

cycle taking into account several navigation and other vehicle data combinations.

- the ***vehicle data*** package is the main data storage. It is decomposed into four sub-packages: *OBC_data, INS_data, CCM_data* and *MPCC-1_data*. Each one consists of data structures definition and its handling procedures.
  - *OBC_data.* Defines several data types corresponding to the different mission states depicted in
  - **Figure** 8. It contains also the SW and HW status and all the timing related data.
  - *INS_data.* Specifies the navigation TM packet and also the command data type to be sent to the INS.
  - *CCM_data (MCC_data).* Specifies the CCMs TM packet (temperatures, voltages, battery status, aileron position, TVA (Thrust Vector Actuator) angle, alarms, engine status, etc.) and also the command data type to be sent to each one (TVA, engine ignition, stages separation, etc.).
  - *MPCC-1_data.* Defines the data types handled by the MPCC-1: CCMs and INS status, CCMs and INS validity and retransmitted frames, CCMs and INS communication establishment commands, etc.

  As an example, the MPCC-1_data package Ada specification is presented in **Figure 12**.
- the ***I/O*** package contains all the services needed to perform the I/O operations for both GCC through the umbilical and MPCC-1 through the VME bus.

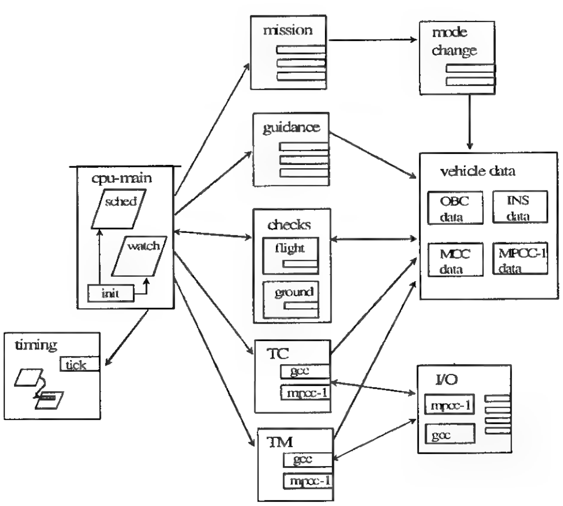

Figure 11: Top-level architectural design

Incremental model

The objective of the incremental development is to obtain the most important functionalities in the first phases of the software life cycle, while the secondary functionalities are implemented later. Software functionalities are stablished into a hierarchy of priorities and grouped in a coherent manner in order to obtain a set of software layers or increments which can run autonomously.

```
package COMUNICACION_MPCC1 is

   type T_TM_MPCC1 is
      record
         ESTADO_COM_MCC_1          : TIPOS.T_SWITCH;
         TRAMA_VALIDA_MCC_1        : TIPOS.T_TRAMA_VALIDA;
         TRAMA_RETRAS_MCC_1        : TIPOS.T_UINT6;
         ESTADO_COM_MCC_2          : TIPOS.T_SWITCH;
         TRAMA_VALIDA_MCC_2        : TIPOS.T_TRAMA_VALIDA;
         TRAMA_RETRAS_MCC_2        : TIPOS.T_UINT6;
         ESTADO_COM_MCC_3          : TIPOS.T_SWITCH;
         TRAMA_VALIDA_MCC_3        : TIPOS.T_TRAMA_VALIDA;
         TRAMA_RETRAS_MCC_3        : TIPOS.T_UINT6;
         ESTADO_COM_MCC_4          : TIPOS.T_SWITCH;
         TRAMA_VALIDA_MCC_4        : TIPOS.T_TRAMA_VALIDA;
         TRAMA_RETRAS_MCC_4        : TIPOS.T_UINT6;
         ESTADO_COM_MCC_5          : TIPOS.T_SWITCH;
         TRAMA_VALIDA_MCC_5        : TIPOS.T_TRAMA_VALIDA;
         TRAMA_RETRAS_MCC_5        : TIPOS.T_UINT6;
         ESTADO_COM_TRAS_TM        : TIPOS.T_SWITCH;
         TRAMA_VALIDA_TRAS_TM      : TIPOS.T_TRAMA_VALIDA;
         TRAMA_RETRAS_TRAS_TM      : TIPOS.T_UINT6;
         ESTADO_COM_PI             : TIPOS.T_SWITCH;
         TRAMA_VALIDA_PI_1         : TIPOS.T_TRAMA_VALIDA;
         TRAMA_VALIDA_PI_2         : TIPOS.T_TRAMA_VALIDA;
         TRAMA_VALIDA_PI_3         : TIPOS.T_TRAMA_VALIDA;
         TRAMA_VALIDA_PI_4         : TIPOS.T_TRAMA_VALIDA;
         TRAMA_RETRAS_PI           : TIPOS.T_UINT6;
         ESTADO_MPCC1              : TIPOS.T_INT16;
      end record;
   for T_TM_MPCC1 use
      record
         ESTADO_COM_MCC_1          at 0  range 0..0;
         TRAMA_VALIDA_MCC_1        at 0  range 1..1;
         TRAMA_RETRAS_MCC_1        at 0  range 2..7;
         ESTADO_COM_MCC_2          at 1  range 0..0;
         TRAMA_VALIDA_MCC_2        at 1  range 1..1;
         TRAMA_RETRAS_MCC_2        at 1  range 2..7;
         ESTADO_COM_MCC_3          at 2  range 0..0;
         TRAMA_VALIDA_MCC_3        at 2  range 1..1;
         TRAMA_RETRAS_MCC_3        at 2  range 2..7;
         ESTADO_COM_MCC_4          at 3  range 0..0;
         TRAMA_VALIDA_MCC_4        at 3  range 1..1;
         TRAMA_RETRAS_MCC_4        at 3  range 2..7;
         ESTADO_COM_MCC_5          at 4  range 0..0;
         TRAMA_VALIDA_MCC_5        at 4  range 1..1;
         TRAMA_RETRAS_MCC_5        at 4  range 2..7;
         ESTADO_COM_TRAS_TM        at 5  range 0..0;
         TRAMA_VALIDA_TRAS_TM      at 5  range 1..1;
         TRAMA_RETRAS_TRAS_TM      at 5  range 2..7;
         ESTADO_COM_PI             at 6  range 0..0;
         TRAMA_VALIDA_PI_1         at 6  range 1..1;
         TRAMA_VALIDA_PI_2         at 6  range 2..2;
         TRAMA_VALIDA_PI_3         at 6  range 3..3;
         TRAMA_VALIDA_PI_4         at 6  range 4..4;
         TRAMA_RETRAS_PI           at 6  range 5..10;
         ESTADO_MPCC1              at 6  range 11..26;
      end record;                                      -- 75 bits


   type T_TC_MPCC1 is
      record
         CMD_ACTIVAR_COM_MCC_1     : TIPOS.T_COMANDO_VALIDO;
         ACTIVAR_COM_MCC_1         : TIPOS.T_SWITCH;
         CMD_ACTIVAR_COM_MCC_2     : TIPOS.T_COMANDO_VALIDO;
         ACTIVAR_COM_MCC_2         : TIPOS.T_SWITCH;
         CMD_ACTIVAR_COM_MCC_3     : TIPOS.T_COMANDO_VALIDO;
         ACTIVAR_COM_MCC_3         : TIPOS.T_SWITCH;
         CMD_ACTIVAR_COM_MCC_4     : TIPOS.T_COMANDO_VALIDO;
         ACTIVAR_COM_MCC_4         : TIPOS.T_SWITCH;
         CMD_ACTIVAR_COM_MCC_5     : TIPOS.T_COMANDO_VALIDO;
         ACTIVAR_COM_MCC_5         : TIPOS.T_SWITCH;
         CMD_ACTIVAR_COM_PI        : TIPOS.T_COMANDO_VALIDO;
         ACTIVAR_COM_PI            : TIPOS.T_SWITCH;
         CMD_ACTIVAR_COM_TRAS_TM   : TIPOS.T_COMANDO_VALIDO;
         ACTIVAR_COM_TRAS_TM       : TIPOS.T_SWITCH;
         CMD_ACTIVAR_COM_MPCC1     : TIPOS.T_COMANDO_VALIDO;
         ACTIVAR_COM_MPCC1         : TIPOS.T_SWITCH;
      end record;
   for T_TC_MPCC1 use
      record
         CMD_ACTIVAR_COM_MCC_1     at 0  range 0..0;
         ACTIVAR_COM_MCC_1         at 0  range 1..1;
         CMD_ACTIVAR_COM_MCC_2     at 0  range 2..2;
         ACTIVAR_COM_MCC_2         at 0  range 3..3;
         CMD_ACTIVAR_COM_MCC_3     at 0  range 4..4;
         ACTIVAR_COM_MCC_3         at 0  range 5..5;
         CMD_ACTIVAR_COM_MCC_4     at 0  range 6..6;
         ACTIVAR_COM_MCC_4         at 0  range 7..7;
         CMD_ACTIVAR_COM_MCC_5     at 1  range 0..0;
         ACTIVAR_COM_MCC_5         at 1  range 1..1;
         CMD_ACTIVAR_COM_PI        at 1  range 2..2;
         ACTIVAR_COM_PI            at 1  range 3..3;
         CMD_ACTIVAR_COM_TRAS_TM   at 1  range 4..4;
         ACTIVAR_COM_TRAS_TM       at 1  range 5..5;
         CMD_ACTIVAR_COM_MPCC1     at 1  range 6..6;
         ACTIVAR_COM_MPCC1         at 1  range 7..7;
      end record;                                      -- 16 bits

   procedure  INICIALIZAR_DATOS_MPCC1 (
                 TM_MPCC1 : IN OUT  T_TM_MPCC1;
                 TC_MPCC1 : IN OUT  T_TC_MPCC1 );

   procedure  INICIALIZAR_TC_MPCC1 (
                 TC_MPCC1 : IN OUT  T_TC_MPCC1 );

end COMUNICACION_MPCC1;
```

Figure 12: MPCC-1_data package specification

The incremental development model has been stablished in the following terms:

1st step:

- communication between GCC and CPU-40.
- communication between CPU-40 and INS.

- communication between CPU-40 and MPCC-1
- vehicle control (staging, MIZAR ignition, ogive separation) under normal conditions.

2nd step:
- roll control during first stage flight.
- guidance during second stage flight.

3rd step:
- cold gas thrusters attitude control from the second stage flight till the end of the mission.

4th step:
- INS data filter
- vehicle control under abnormal conditions

8 GROUND CONTROL COMPUTER

The main GCC functions are [9]:

- Vehicle Initialization and Pre-Launch Tests. GCC commands initialization of Cold Gas system and TVA by opening the respective tank valves through pyrotechnical mechanisms. It also commands alignment and navigation start of INS, and pre-launch tests of TVC and ailerons.

- Provide a proper operator interface. It shows the telemetry data in a clear way using graphs, gauges, tables, etc. to make them easier to understand and simplify the troubleshooting procedures. To send a command the user has to press simply one button. If the command requires some parameters, a dialog box appears to the user to ask the values and control the coherence and the range of all parameters. This easy way of controlling eliminates any error from the operator and does not require complex operations or additional hardware to be used.

- Register pre-launch sessions. Records each received data frame and provides tools to replay registered sessions in order to review problematic situations.

- Print output. Trace major events in a paper report.

- Integration tests. GCC is not only used to monitor vehicle health during pre-launch phase but also to monitor stages health prior to vehicle assembling.

The adopted solution is a system entirely implemented using the graphic development tool LabVIEW® by National Instruments™ on a PC environment running Microsoft® Windows 3.11.

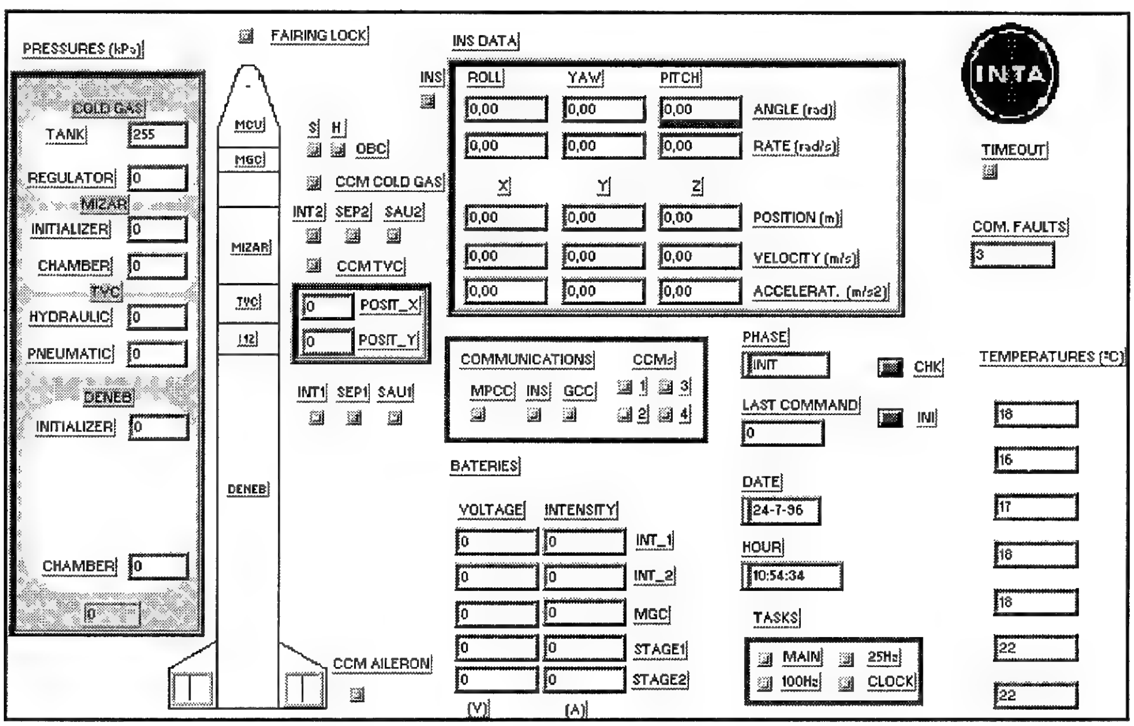

Figure 13: GCC software prototype layout

A prototype of the GCC software has already been done (**Figure 13**) and evaluated by the user (Rocket Motors Laboratory personnel) outstanding the following advantages and drawbacks:

Advantages

- quick development
- nice looking and easy to reconfigure interface
- easy understanding of data
- easy management of commands

Drawbacks

- **Limited speed performances.** It was not easy to deal with a 150 bytes frame at 25 Hz and a rate of 38000 kbits/s, provided it was both processed and recorded. However, the feeling is that this problem could be easily solved applying several strategies: increase computer power, reduce vehicle communications frequency during pre-launch or even link C communication routines to the LabVIEW® application.

- **Processing algorithm modifications become harder to implement as the application grows.** This problem is highly influenced by the Graphical Programming Language of LabVIEW® which turned out to be much less flexible than a conventional High Order language written by means of a text editor.

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Signature Avionics - Signature Optimised Operating of a Stealth Aircraft

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1 Summary

Stealth design is one design principle for next generation combat aircraft. The effort in this area have a long history at the Daimler-Benz Aerospace (Dasa), formerly MBB, e.g. the Lampyridae project in the early 80's.

Operational studies have shown that the introduction of stealth design will increase the survivability of combat aircraft significantly, especially against airborne threats. Yet the effective use of critical signatures during a mission and the matching of tactics to stealth features require the development of an adapted avionics.

This adapted avionics - signature avionics - will

- not compromise the stealth design,
- take direct advantage from the stealth characteristics,
- and utilise the stealth properties via an integrated tactical mission control.

To transform this idea into an applicable format suited for the implementation in aircraft avionics systems

- a functional breakdown in individual functions,
- prototyping and performance analysis of these functions,

turns out to be necessary.

The feasibility of this approach has been proven on the signature avionics function „fly by signature" as an example.

2 Introduction

Low observability appears as one of the prominent features for next generation combat aircraft.

Studies at the military division of Daimler-Benz Aerospace (Dasa-LM) - as well as elsewhere - prove the operational utility of stealth designs. However, these studies show also that a stealth design alone is not sufficient to protect the aircraft in a hostile environment. Low observables must be accompanied by appropriate avionics - "signature avionics".

Signature avionics refers to the adaptation both of hardware and software. The multiple interactions between vehicle and avionics systems in a mission require a comprehensive approach with many aspects to be considered. For example, uncontrolled electromagnetic emissions from avionics components (radar, missile approach warner, etc.) can jeopardise the advantages gained from a low signature design, but mission needs must be fulfilled and appropriate tactics should reconcile the differing objectives.

The realisation of signature avionics with respect to software is via correlated functions: the signature avionics functions (SAFs). The content of SAF is determined by the scenario, its threats and the aircraft and its mission.

Experimental and theoretical methods are required to analyse the complex interrelations between stealth design and avionics. In this paper we describe how SAFs are developed, analysed and evaluated at Dasa.

The paper is organised into 5 further chapters:

- Chapter 3 is meant to motivate the issue.
- Chapter 4 discusses signature avionics in greater detail.
- Chapter 5 describes tools for signature avionics development and evaluation at Dasa.
- Chapter 6 elucidates the elements and the operation of the SAF „Fly by Signatue".
- Chapter 7 gives a short résumé.

3 Motivation

Stealth design concepts have a long history at Dasa, formerly MBB. An example is the Lampyridae project for a stealth fighter in the early 80's paralleled and followed by a number of studies.

Operationally in terms of survivability and effectiveness in penetrating missions these analyses show that

- with respect to ground based air-defence, low flight altitudes dominate low radar cross section in a dense threat environment. Terrain masking limits the effect of signature reduction (see figure 1), but additional benefits can be envisioned via tactics adapted to the signature characteristics.

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- even a very low radar cross section (RCS) does not allow for a safe penetration at medium/high altitudes on its own, without additional measures.
- against airborne air defence, a significant reduction of radar cross section is effective (however improvable), if airborne air defence relies on active radar only (see figure 2).
- if the air defence side exploits on other signatures of the penetrating aircraft, low radar cross sections may be compensated for.

The spectrum of other signatures comprises

- the infrared signature,
- the visual signature,
- the acoustic signature,
- active electromagnetic emissions,
- inadvertent electromagnetic emissions.

In the context of penetrating missions by low RCS vehicles against ground based and airborne defences these signatures may be qualified as follows:

- Except for high altitudes of both sensor and target and/or high target speeds, IR-sensor ranges remain in the order of magnitude of radar ranges in frontal target aspects.
- Visual ranges are even shorter.
- Due to the dependence of the sound velocity on the atmospheric conditions it is difficult to use the acoustic signature for locating the target timely and precisely enough for effective counteractions.
- Active electromagnetic emissions, e.g. from radar, altimeter, missile approach warner, data links, communications, allow for long range all-weather detection and angular measurements and, with already existing sensors, can re-establish air defence early warning coverage. Moreover the locating capabilities of these sensors are sufficient for timely alert and guidance of air defence assets. Accuracies are good enough to direct air defence systems up to the point where they can use their acquisition and fire control sensors.
- With respect to inadvertent electromagnetic emissions, no operational sensors are known to us, but efforts to counter the stealth approach can result in sensors with capabilities comparable to the above.

Therefore, two goals rate high in priority:

- denying the threat the use of critical signatures during the mission
- drawing additional benefits from matching tactics to stealth features.

We believe that both aims can be achieved by the above mentioned signature avionics approach.

To achieve these objectives, the avionics systems have to be analysed carefully for extensions to harmonise with and to support the stealth design of the aircraft.

4 SIGNATURE AVIONICS

Referring to the motivation given above, there will be specific requirements to the avionics systems in the case of a stealth design of the aircraft. Avionics components and subsystems as well as their operation must be designed to meet the objectives:

(1) Avionics that do not to compromise the stealth design by:
   - spoiling the RCS signature
   - active electromagnetic emissions

(2) Avionics that take direct advantage of the aircraft´s stealth characteristic,

(3) Avionics through which stealth design and avionics functions are co-ordinated by integrated tactical mission control.

Figure 1: Aircraft losses due to ground based air defence

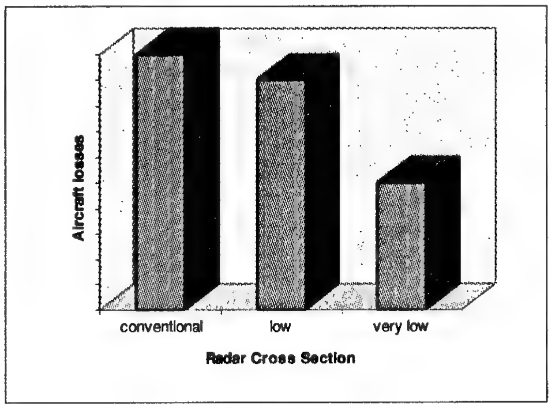
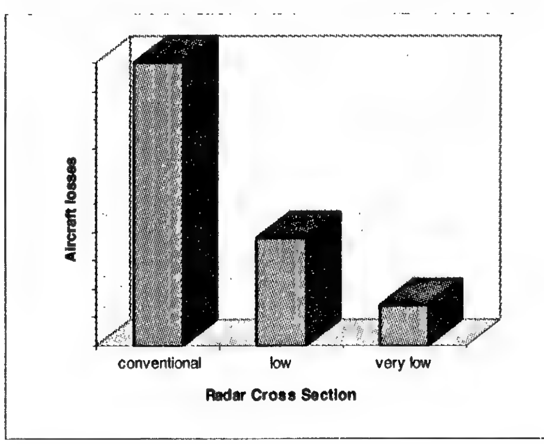


Figure 2: Aircraft losses due to airborne air defence



Without attempting completeness, implications are as follows:

(1) Not to compromise stealth design

Component design and integration (e.g. sensor apertures, internal weapon bay and its operation for weapon release) not increasing the signatures in critical aspects; operation of emitting sensors controlled in time, space, energy, waveform in the mission context, allowing for the employment of

active sensors only if indispensable, e.g. for target acquisition in adverse weather conditions, giving minimal information to the threat.

(2) To take direct advantage

The strong anisotropy of the radar cross section of a stealth aircraft offers a new degree of freedom that can be tactically exploited via manoeuvring e.g. to exhibit the minimal RCS to the threat. This requires the knowledge of the aircraft signature and of the operation and lethality of the hostile weapon systems.

(3) Integrated tactical mission control

New tactical concepts and mission profiles require a tactical mission controller for:

- information gathering/sensor operation
- situation assessment and tactical decision making
- timing of transmissions
- routing/re-routing, tactical manoeuvring
- employment of ESM and ECM systems

Breaking down this new avionics system in a functional manner leads to signature avionics functions (SAFs).

Examples are:

- information management, data fusion and cueing for passive and active sensors and external sources.
- new means of navigation, e.g. introduction of a 3D terrain data base in connection with GPS (global positioning system).
- emission management, i.e. situational emissions, power management by spatial and temporal limitations of emissions.
- introduction of data compression and spread spectrum methods concerning communication,
- adaptive camouflage.

5 Development and Evaluation of Signature Avionics Functions

Figure 3 schematically shows how signature avionics functions are realised. From aircraft characteristics, system requirements and for the mission scenario environment, the definition of SAFs comprises

- prototyping and performance analysis,
- software (SW) development,
- evaluation, ranking and selection,

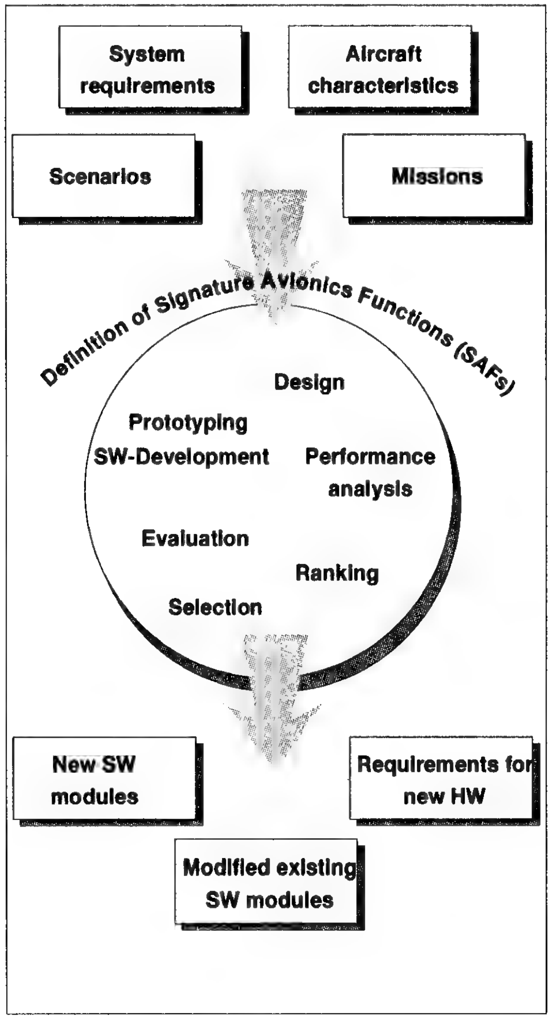
resulting in new software modules, requirements for new hardware and modifications to existing software.

Four main tasks arise:

- Identification and specification of possible candidates for avionics functions necessary for the aircraft to utilise its stealth properties.
- Development of the identified avionics functions by rapid prototyping to create software modules that can be integrated in a simulated or real avionics system.
- Test and evaluation of the developed software with respect to operational utility and compatibility with other avionics subsystems.
- Ranking of the different signature avionics functions developed and selection of the most promising candidates.

To achieve short cycles of software development on the one side and to check the compatibility and performance of the software representing the SAF on the other side, the development environment described in the following chapters has been set up.

Figure 3: Objectives for the development of SAFs



5.1 Development

The key to the development of an operational signature avionics subsystem is a stepwise approach setting out from rapid prototyping on workstations, transferring to ground based demonstrators, increasing 'hardware in-the-loop' components (including operational software) and aiming for in-flight verification.

Rapid prototyping of the software modules is performed in the Dasa Software Technology Environment consisting of a cluster of Symbolics and Silicon Graphics workstations. During this development of the software modules, existing models of terrain, threats, radar signatures, vehicles, etc. are used. Initial testing of the software modules with respect to behaviour and numerical stability is also performed in the Software Technology Environment.

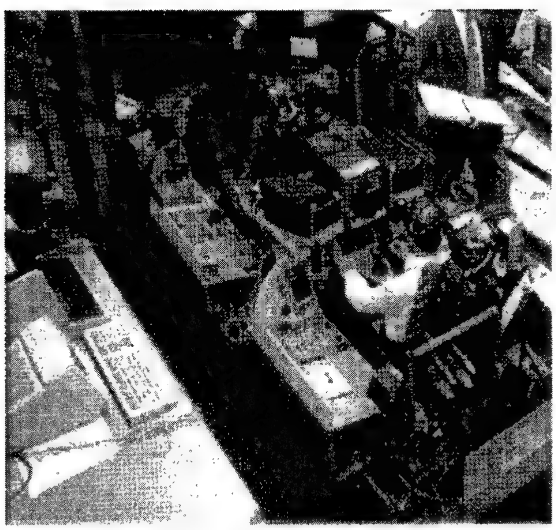
In the next step the software modules representing a specific signature avionics function are integrated in the Avionics Testbed, shown in figure 4. This Avionics Testbed consists of an experimental cockpit equipped with

- various display and interaction capabilities.
- control elements like stick, pedals, throttles.
- simulated external view.

and a real-time flight control system

- to model the vehicle manoeuvres.
- to transform pilot inputs into steering and control values.
- to provide simulated navigation data.
- to provide autopilot functions.

Figure 4: Avionics Testbed



Actually the Software Technology Environment is linked to the Avionics Testbed via Ethernet. In this environment the interaction of signature avionics functions with other avionics functions and the man-machine interface can be studied.

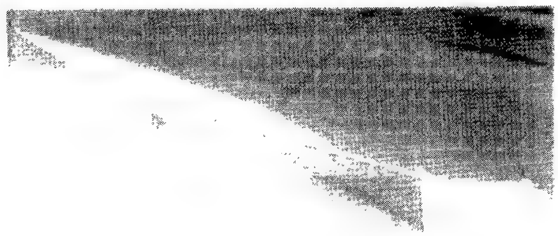
Optionally, the development phase can be rounded off with a test phase in a flying testbed, e.g. in a stealth aircraft as shown in figure 5.

5.2 Evaluation

Whereas the evaluation of SAFs in terms of overall mission effectiveness and survivability remains in the domain of Operational Analysis, evaluation in the above described context aims for specific questions such as:

- What is the operational benefit of the SAF component currently under development alone and/or in combination with other SAFs ?
- How will the SAF interact with other avionic systems in an aircraft, in particular the man machine interface ?

Figure 5: Airborne Demonstrator



Operational performance is verified and evaluated mainly in the Software Technology Environment by simulation. In a context including

- different threat systems with various deployments.
- 3D terrain data,
- 3D flight paths,
- terrain masking effects,
- aircraft performance characteristics,

the penetration of the stealth aircraft is simulated and the interaction of the threats with the aircraft is traced and analysed in detail. An example for this is given in chapter 6.

To demonstrate the interaction of the SAF with the avionics system the Avionics Testbed with its functions close to reality is used together with the Software Technology Environment. In this aircraft type environment the correctness of data exchange, the timing and the functionality of the man machine interface are evaluated. The results of different flights are recorded and can be rehearsed afterward with respect to operational issues in the scenario simulation described above.

6 Example: Fly By Signature

To demonstrate the above discussed development process at Dasa, Fly by Signature has been picked as an example which exhibits a number of the elements involved in SAFs:

- mission and threat representation.
- terrain.
- vehicle manoeuvres.
- radar cross section characteristics.
- on-board sensors.
- route optimisation algorithms accounting for threat avoidance, terrain masking, RCS relative to threat sensor performance and system lethality.

6.1 Principles of Flight Path Optimisation

For a better understanding of the flight path optimisation approach for a stealth aircraft, the basic principles are outlined for a less challenging example: planning an optimised route without consideration of RCS.

A scenario is set up by placing SAM sites in a terrain model (see figure 6, with threat positions marked by letters and missile ranges shown by circles). For a specific flight level the areas visible to the different threats are calculated. For the regions not masked by terrain "danger arrays" are attached according to the threat type. Multiple threats are cumulated. (See figure 6 with darker grey indicating higher threat levels).

For given start and end points the optimised route is derived by minimising the integral over the "danger areas" with constraints imposed by the flight control system. In figure 6 the optimised route is shown as a dotted curve.

Figure 6: Flight path optimisation for conventional aircraft

6.2 Principle of Evaluation

The criterion for flight path evaluation is the susceptibility of an aircraft flying through such a scenario with different threats. For each SAM site the track possibility will be calculated and the time an aircraft is exposed to it gives an indication of the risk.

In figures 7 and 8 this track capability is shown for two different flight paths by monitoring the lock-on intervals (shown by dark areas).

6.3 Models

Computationally, the above example is based on a threat radar model describing the radar performance and its rules for moding as well as a target model describing the radar cross section and its fluctuation.

Figure 7: Acquisition (a) and track (b) probability for a „Fly by Signature" - flight path

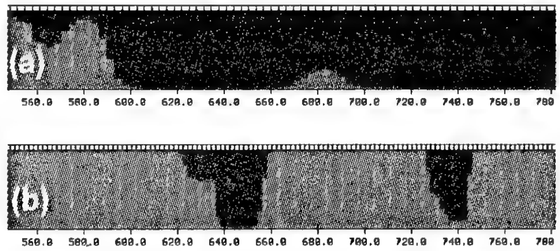
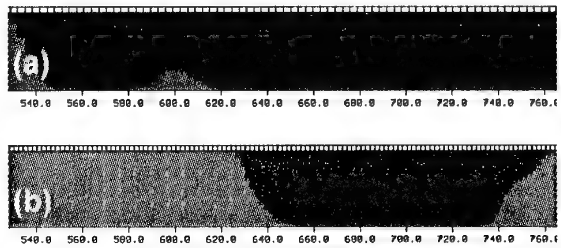


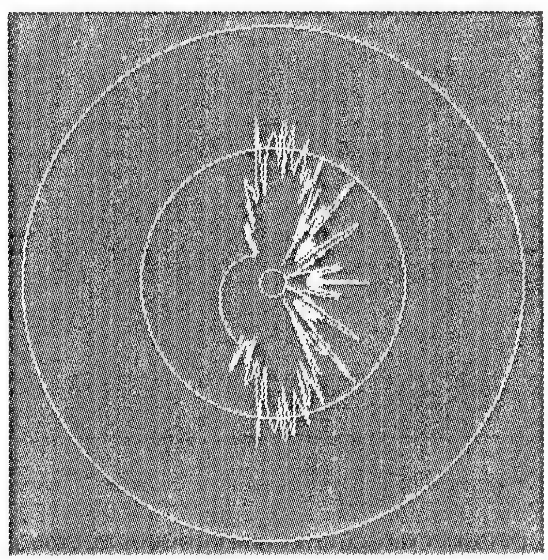
Figure 8: Acquisition (a) and track (b) probability without flight path optimisation



Target Model

Figure 9 shows a typical radar cross section (dB scale, only zero elevation shown) for a stealth aircraft. For the purpose of flight path optimisation the statistical fluctuations of the aircraft are taken into account by smoothing the RCS (Fig. 10) and applying Swerling I statistics.

Figure 9: Calculated RCS of a stealth aircraft



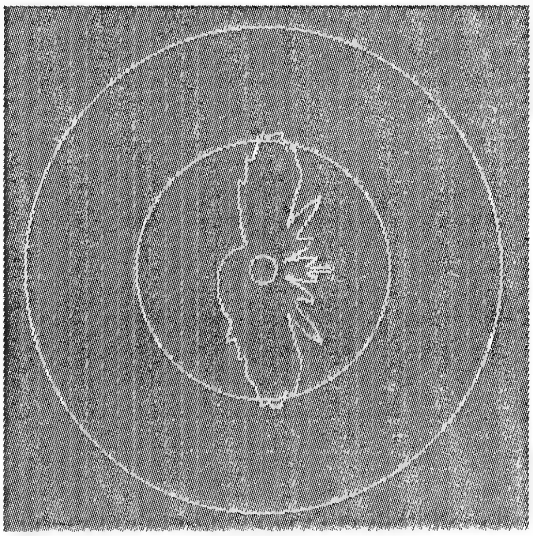
Threat Model

We assume that the threat systems operate both with acquisition and track radars.

The acquisition radar scans a sector and its main beam will (almost) periodically hit the target when it is inside the sector.

As an example, figure 11 shows the performance in terms of single scan detection probabilities of the acquisition radar for various radar cross sections.

Figure 10: Smoothed radar cross section



Detection is modelled via cumulation of single scan detection probabilities with upper and lower thresholds. The detection state is reported for evaluation on the one hand (see figure 7, 8) and triggers the employment of the track radar on the other hand.

Figure 12, in analogy to figure 11, outlines the performance of such a tracking radar in terms of single look detection probability.

Figure 11: Single scan detection probability for an acquisition radar

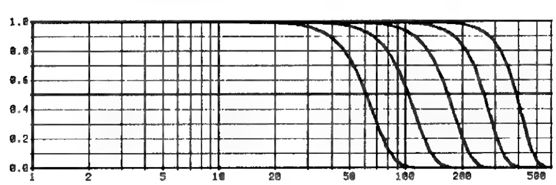
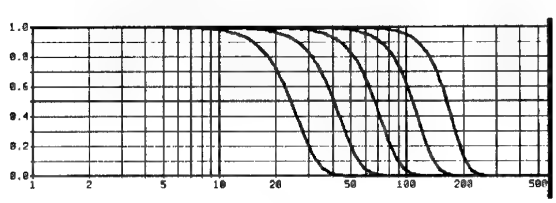


Figure 12: Single scan detection probability for a track radar



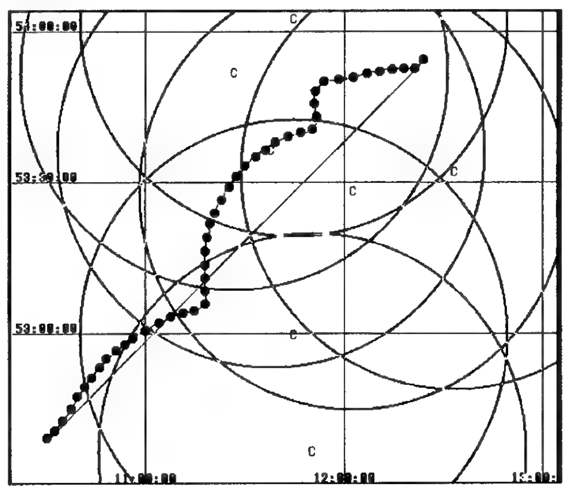
Track initiation is started by "handover" from the acquisition radar. Based on the cumulated detection probability a track quality parameter is recorded and used to determine the threat level and lock-on state via thresholds. Lock-on together with time delays means the threat is ready to launch a missile.

Therefore the reduced duration of lock-on states is the primary pay-off for route optimisation.

6.4 Typical result

For a scenario in flat terrain, consisting of 7 identical threats, the result of the flight path optimisation for a trajectory from the south-west to the north-east, is shown in figure 13. Threat sites are marked by letters, missile ranges by circles, the resulting flight path by a dotted line. This flight path takes aircraft performance and flight-control system constraints into account. Speed is 250 m per second, and compared to the shortest route the flight time increases from 800 to 900 seconds.

Figure 13: Result of flight path optimisation



The flight path derived from flying by signature shows - on the first glance somewhat unexpected - a cycloid type shape.

When comparing a straight line to the „Fly by Signature" flight path it turns out that without optimisation each of the seven threats builds up lock-on intervals exceeding one minute (see figure 8). With optimisation

- 3 of the 7 threats do not achieve a stable track and hence would not be able to launch a missile against the aircraft,
- For 3 of the remaining threats lock-on time is reduced by a factor 2 or more (see figure 7),
- For one threat however, no significant improvement arises.

In this case a high subclutter-visibility was assumed for the radar. Lower subclutter-visibility would improve the result as long low-radar cross sections are exposed.

7 CONCLUSION

Stealth design for penetrating aircraft improves their survivability. However, to take full advantage of low signatures, the implementation of adapted avionics - signature avionics - is required.

Due to the manifold interactions of stealth design with the avionics system a functional breakdown resulting in signature avionics functions has turned out to be necessary to identify the avionics areas affected.

Due to new requirements emerging from the stealth aircraft characteristics, careful prototyping of these signature avionics functions in conjunction with a careful and accurate evaluation of their performance is mandatory. Suitable prototyping and assessment environments have been built up during the last years at Dasa-LM and have proven their usefulness.

In our view, signature avionics is an essential element of future combat aircraft.

A Multiservice Switch for Advanced Avionics Data Networks

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Abstract

With knowledge of persistent data communication traffic patterns offered to an avionics data network, modifications to the routing through the network can be made to improve total throughput and bound the latency of packets. The Multiservice Switch (MSS) is such a route-optimizing switch for streaming sensor data. The MSS has two switching fabrics: packet switching and circuit switching. The packet-switching fabric routes small control and data packets between switch ports. The circuit-switching fabric uses a crossbar to physically connect ringlets, which reduces the workload on the packet-switching fabric for long data streams between the ports.

An implementation of the MSS is described which uses commercial-off-the-shelf (COTS) components. A simulation model was developed to show the benefits of the MSS under standard avionics workloads. The results of the MSS indicate distinct advantages in terms of performance, price, and power consumption over other conventional switch and network topology designs.

Introduction

A number of recent studies have identified a requirement for a unified avionics data network that is capable of replacing a variety of existing interconnects such as the Parallel Interface (PI) Bus, Data Network/Data Flow Network (DN/DFN), High Speed Data Bus (HSDB), and Sensor Data Distribution Network (SDDN) [UHLH92][SAE93]. For example, studies performed under the Air Force PAVE PACE and Very High Speed Optical Networks (VHSON) programs have shown that by integrating the functionality of the DN/DFN, PI Bus, HSDB, and sensor/video network into a single network, the reliability of the interconnects could increase by a factor of 13 while reducing cost by 50%, weight by 60%, and power by 70% [ULHL92]. As a result, system designs such as the Joint Strike Fighter (JSF) preferred concept feature a unified network as an essential component of the architecture [JAST94].

One of the difficulties impeding the implementation of a unified network is the development of a data switch capable of supporting the conflicting requirements of the networks being replaced. For example, PI Bus traffic is characterized by short, low-latency messages which would best be handled by a connectionless, packet-switched transfer whereas DN/DFN traffic is characterized by stream data best handled by a connection-oriented, circuit-switched network. Sensor data is a mix of the two in that it is mostly stream data interrupted occasionally by very-low-latency, high-integrity control and status information.

In this paper we describe the development of a compact, low-power multiservice switch capable of supporting both connectionless and connection-oriented transfers. The switch operates at a 1-Gbps serial data rate and the inputs and outputs are optical. The switch is based on the IEEE 1596-1992 Scalable Coherent Interface (SCI) standard [SCI93]. This standard supports a number of interconnect topologies including ringlets, switched networks, and ringlets interconnected by switches which make it suitable for multiservice transfers. The MSS provides multiservice support by incorporating a crossbar switch which reconfigurably interconnects ringlets to form larger ringlets. In addition, each input port is connected by a back-end bus which reroutes messages addressed to nodes on other ringlets. Stream data transfers are supported by connecting the source and target nodes on a common ringlet via the crossbar switch, while small, bursty transfers are supported via the back-end bus.

The advantage of this topology is that the back-end bus is only used to transfer relatively short control and status messages, so that very-low latency can be achieved for these messages. An added advantage is that the power, size, and cost of the switch are much lower than in a switch that must provide high-speed, exclusively-connectionless transfers. In the next sections we describe the functional design of the switch and predicted performance and power dissipation for a 5-port (4 SCI ports, 1 control port) prototype currently undergoing test and evaluation. This switch is based on the Dolphin LC-1 link controller chip which uses interval routing. We also describe the results of simulations that predict the performance of a switch based on look-up table routing which would provide greater system flexibility. Finally, brief conclusions are drawn about the performance and utility of the multiservice switch.

SCI Overview

SCI is a unidirectional, point-to-point, high-performance network protocol with a standard bandwidth of 1-GBps and a media access control using register insertion ring for low-latency concurrent transfers. SCI is a synchronous protocol and emits a single 18-bit symbol at each clock cycle. SCI packets are made up of a series of delimited symbols. The internal structure of an SCI node is shown in Figure 1.

Incoming SCI packets arrive and are routed either to the input queue or to the bypass FIFO by the stripper based on the destination address of the packet. The host interface services the input queue and offers new packets into the output queue. A multiplexer arbitrates between the bypass FIFO and output queue for transmission onto the SCI ring.

Paper presented at the AGARD MSP Symposium on "Advanced Architectures for Aerospace Mission Systems", held in Istanbul, Turkey, 14-17 October 1996, and published in CP-581.

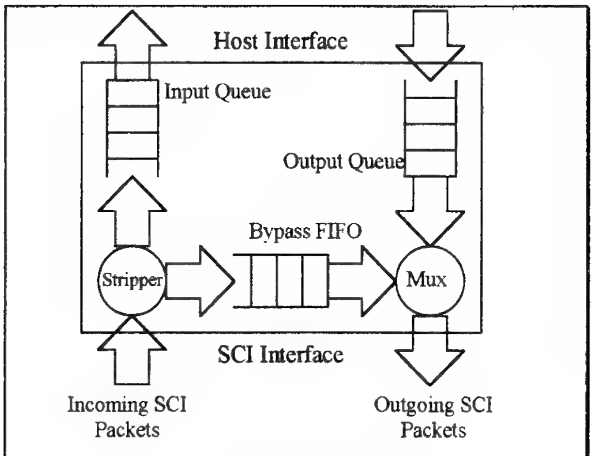

Figure 1: SCI Node

Common SCI topologies are ring-based so that packets are passed through the bypass FIFOs of intermediate nodes on their way to the destination node. Although rings are the easiest topology to create using SCI nodes, they suffer from a lack of fault tolerance and a minimum latency proportional to the number of intermediate nodes. SCI switches are used to connect separate SCI rings in an attempt to increase both fault tolerance as well as improve performance by routing packets out of rings to save bandwidth. Switches have a penalty of routing delay, which is necessary for all packets that are routed by the switch. Certainly a trade-off between the performance improvements of a switch and the streaming performance of the ring can be made.

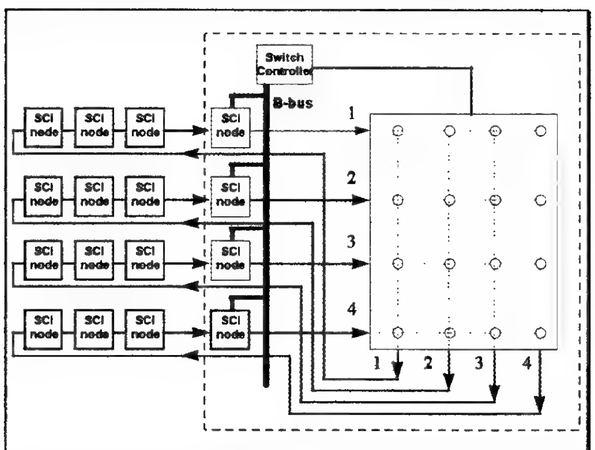

Figure 2: Block Diagram of Multiservice Switch

Switch Design

Figure 2 shows a functional block diagram of the multiservice switch. The default configuration has the crossbar simply passing packets from the same numbered input port to output port. Figure 3 shows a schematic of an individual port inside the switch. Each port on the MSS is connected to an SCI ringlet consisting of several nodes. The serial optical input signal at each port is converted to an electrical signal and inputted to an Hewlett Packard G-Link chip for deserializing and decoding. The parallel format is required for SCI node interface (i.e. the Dolphin LC-1) that receives it next. The output of the LC-1 is encoded, converted back to serial, and sent to one of the inputs of a serial, electronic-crossbar switch. The corresponding output of the crossbar is converted to an optical signal and routed to the output of the port, where it completes the ringlet. The crossbar switch is controlled via a parallel port which may be attached to a host processor connected to any node on the network. The same host controls the initialization and status of the LC-1 chip at each port via separate control logic. The node interfaces at each port are connected together via a back-end bus (i.e. the B-bus in Figure 2). Packets addressed to a ringlet other than the one to which the port is connected are stripped from the ringlet by the interface circuit and routed to the appropriate ringlet via the back-end bus.

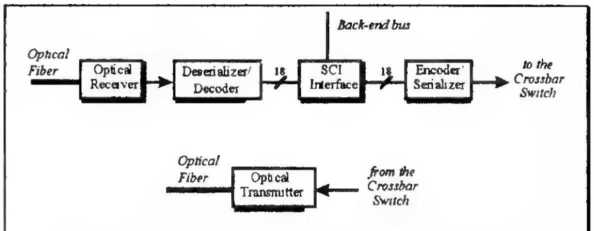

Figure 3: Multiservice Switch Port Schematic

Individual ringlets may be connected together through the crossbar switch to form a single ringlet. For example, if the crossbar switch is configured so that input 1 is connected to output 4 and input 4 is connected to output 1, all of the nodes in ringlets 1 and 4 actually reside on a common ringlet. A typical configuration might consist of a sensor on one ringlet connected to a second ringlet comprised of a suite of processing and memory modules. Stream data from the sensor is transferred to the processing suite through the crossbar switch. Short control and status messages from or to nodes residing on different ringlets are transferred over the back-end bus. Since only the low-data-rate control and status messages are transferred over the back-end bus, very-low latency for these messages can be achieved.

In normal operation reconfiguration would occur only in the case of component failure, battle damage, or change of mission. A reconfiguration may be initiated by any node by sending a request to the node controlling the crossbar switch. If the request is valid, this node instructs the interface circuits at the switch ports to begin issuing reset commands around the affected ringlets. The crossbar switch is then set and the affected ringlets are allowed to reinitialize in the standard way. During initialization new node IDs are assigned to each node if necessary. The entire process is estimated to take less than 1 ms. In comparison, the SAE requirement for reconfiguration of an SDDN is 50 ms [SAE93].

The current prototype operates at a serial data rate of 1-Gbps. This rate is limited by the speed of the crossbar switch. If a faster electrical or optical switch were available the ultimate speed of the switch would be 1.6-Gbps, limited by the speed of the interface circuitry. The back-end bus operates at an aggregate data rate of 3.2-Gbps.

The power dissipation of the switch may be estimated from the individual components. Each port consists of an optical transceiver, a serializer/deserializer, interface circuit, and assorted line drivers. Total power dissipation for these

components is 11.15 W. In addition, the crossbar switch and control logic dissipate 5.4 W. Total power dissipation for the 5-port prototype is estimated to be 61.15 W. A 16-port version would dissipate 183.8 W.

Simulation Descriptions

The following sections provide descriptions of the models that were created to simulate the SCI protocol and different SCI switches to measure the performance of complete systems. The SCI emulation model provides the basic SCI transport operations in a fine-grain manner. The switch models extend the emulation model to simulate a packet-level switch as well as the MSS. Three example systems are presented and network loading scenarios are described to show the relative benefits of each of the topologies. Finally, results of the simulations are presented and analyzed.

SCI Emulation Model

The SCI emulation model was designed and implemented using the Block-Oriented Network Simulator (BONeS) from the Alta Group of Cadence Systems, Inc. BONeS is a discrete-event simulator with many built-in modeling blocks for fine-grain network simulation. The SCI emulation model was designed to follow the SCI standard as closely as possible, sacrificing minimal fidelity to improve simulation speed. The model has many parameters that can be set to match experimental measurements of existing SCI hardware. In this way, specific hardware implementations can be simulated by calibrating the model using these parameters.

The model was built to be generic and reusable although some design parameters were assumed. First, packet routing is of prime importance when modeling any switches. The SCI node routing decisions are made by table lookups of routing tables which are dynamic and can be rewritten during simulation if reconfiguration occurs. Generic routing tables can also simulate static-routing schemes such as interval routing. A symbol-level simulation is most desirable for fidelity purposes but can lead to extremely long simulation times. Instead, two modeling techniques were used to improve simulation time. First, any output symbols of a contiguous SCI packet are clumped together. In this way, only one event is triggered once a packet is received instead of the 40 events for a 40- symbol send packet. Second, the packet undergoes a "pipelined" delay during reception. This technique forces the receiving node to delay until the needed symbol of the packet arrives before it is allowed to use the information. In this way, exact bypass and routing delays can be simulated with great accuracy.

Each node has an adjustable clock frequency and is assumed to output a single 18-bit symbol during each clock period. Hence, serial SCI nodes can be simulated by appropriate clock frequency selections. The node's host interface is separately clocked to simulate a different speed host. The host interface was designed to support either an asynchronous or synchronous host. An asynchronous host offers traffic at an arbitrary rate and will process rejected packets if the output queue is full. An asynchronous host will attempt to service the input queue as quickly as possible. If the host is not available, the host rejects the incoming packet which is pushed back into the input queue. If the host cannot service incoming packets at a sufficient rate, the input queue will fill which forces new packets to be retried using SCI's queue reservation protocols for retried packets.

Synchronous hosts offer packets at a constant rate to the output queue and service packets at a constant rate from the input queue. This mode of packet handling simulates constant rate sources such as sampling sensors and constantly-polled input sinks. The modeled interface was designed in such a way to support both timing methods simultaneously.

SCI Switch Models

A packet switch is shown in Figure 4 and is built of multiple SCI nodes. The host interfaces of the nodes in the switch are connected to a common fabric such as a shared bus.

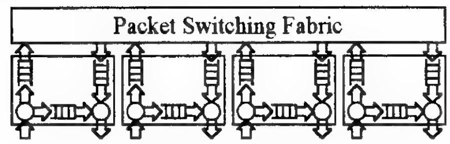

Figure 4: SCI Packet Switch

The MSS is built by combining a packet switch with a crossbar to allow switching of physical circuits. This design is shown in Figure 5. Notice that once rings are combined using the crossbar, the SCI nodes inside the switch simply pass packets destined for a node on the new ring through their bypass FIFOs instead of stripping them off and passing them over the packet switching fabric.

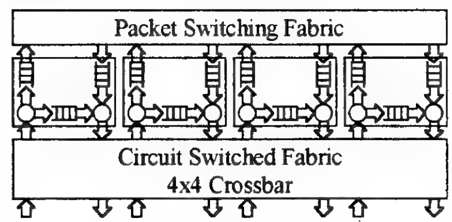

Figure 5: SCI Multiservice Switch

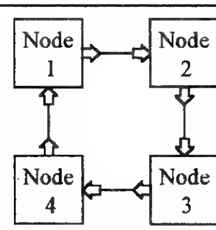

Figure 6: 4-Node SCI Ringlet System

Simulated Systems

A simple SCI ringlet system, shown in Figure 6, was used as a baseline for comparisons of latency, throughput, and response time variance. The ringlet is formed by connecting the output link of one node to the input link of the following node and requires no additional hardware. A system of 4 nodes connected with a packet switch was used to verify the routing performance of the switch. The packet switch system is shown in Figure 7.

This configuration offers a separate ringlet per node and requires a high-performance, packet-switching fabric to maintain high throughput. Finally, a system built with an MSS is shown in Figure 8. The configuration is isomorphous to Figure 7, as the MSS is topologically identical to a packet switch.

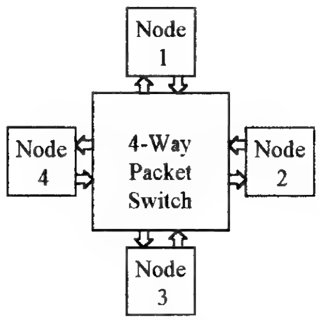

Figure 7: Connectionless Switch System

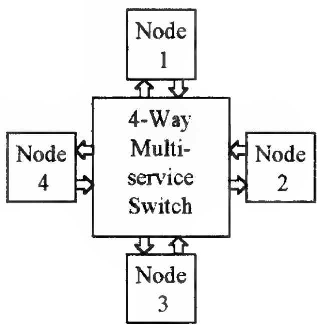

Figure 8: Multiservice Switch System

Simulation Scenarios

In order to gauge the effectiveness of the multiservice switch, the three systems described above were implemented in the simulation environment. Each node of the system was configured with a statistical requester and an active responder. The requester has four types of parameters that can be varied to simulate certain classes of data sources: request type, interarrival type, burst type, and destination type.

- The *request type* specifies which commands this requester will generate and at what size. Common commands are read, write, and move with standard payload sizes of 64 or 256 bytes per request. A read command requests a certain block of memory from the responder, which generates a response packet with the data. A write command passes a block of data to the responder to write into memory. The responder replies with a response packet once the data has been committed into memory. A move command writes data from the requester to the responder but eliminates the response subaction.

- The *interarrival type* specifies the time between subsequent requests. Available interarrival rates are fixed or random with uniform, exponential, or normal distributions. The mean and variance can be specified.

- The *burst type* specifies how many requests are generated in a stream from this requester. The number of requests can be fixed or random with uniform, exponential, or normal distribution, again with mean and variance as parameters.

- The *destination type* specifies where requests from this node will be sent. The available destinations are fixed, random with uniform distribution, downstream (next node on ring), upstream (previous node on ring), and self.

By selecting the appropriate parameters of the source, different loading conditions on the network can be investigating in hopes to predict actual performance. Parameters that specify SCI node performance can also be varied and reasonable choices were chosen. Table 1 lists the externally-variable node parameters and the values chosen throughout all simulations.

Table 1: SCI Simulation Parameters

Parameter	Description	Value
Input Queue Size	Number of packets that can be stored in the input queue	3
Output Queue Size	Number of outstanding transactions	3
Link Data Rate	Speed that raw data is passed over SCI	1.6 Gbps (i.e. 200 MBps)
Host Data Rate	Speed that raw data is passed from the SCI node to the host	1.6 Gbps (i.e. 200 MBps)
Switch Data Rate	Speed that raw data is passed through the packet switching fabric	3.2 Gbps (i.e. 400 MBps)
Stripping Delay	Symbols necessary to determine packet destination, w/ no routing table check	2 symbols
Routing Table Delay	Symbols necessary to delay while checking the routing table	40 symbols (store and forward switches)
Link Length	Length of electrical wiring runs between nodes	3 meters

Each of the three network configurations was offered the three following loading conditions to allow a fair comparison between the topologies. Table 2 summarizes in qualitative terms the expected results of the simulation.

1. The first loading condition is a streaming test. This involves two nodes (the first and the fourth) in which node 1 sends 64-byte move packets to node 4 at a fixed rate. The throughput and latency is calculated at the responder node. This test forms the upper bound in throughput for the

specific topology. The switched MSS system performance is expected to match the ringlet system while the packet switched system will have a slight decrease in throughput due to routing delays.

2. The second loading condition offers a varying total offered load to each system where each node sends a fixed burst length of read and write requests to a random responder with a Poisson distributed interarrival rate. The latency and throughput is measured at the requester since reads and writes are response-expected transactions. The ring performance is expected to be poor since the ring bandwidth is fairly shared among all 4 nodes. The two switches are expected to perform identically since the MSS gains no advantage of circuit switching under random traffic. The switched systems will enjoy a much higher aggregate throughput than the ring system due to the separated ringlets.

3. The final loading condition combines the first two to mimic a typical avionics sensor-processing workload. Node 1 is specified as a source node and streams data to node 4. Simultaneously, all nodes except node 1 send out fixed burst messages to random destinations. The streaming load is made up of 64-byte move transactions and is representative of sampled data from a sensor. The random load is typical of control messages and uses an exponential interarrival rate to simulate computer-generated traffic. The streaming data is designed to utilize 10 times the bandwidth of the combined random load. Actual SAE specifications cite streaming loads up to 2-Gbps and control loads up to 1-MBps, a 200:1 ratio [SAE93]. In this final case, the MSS should show the streaming performance of the ring and the bursty performance of a switch while the packet switched system and the ring system will perform worse due to topological constraints.

Table 2: Qualitative Expected Results

	Streaming	Random	Mixed
Ring	Good	Poor	Poor
Packet Switch	Poor	Good	Poor
MSS	Good	Good	Good

Simulation Results

The simulation results are grouped into sections based on the three loading conditions. The first set of graphs shows the throughput and latency for the streaming-load scenario.

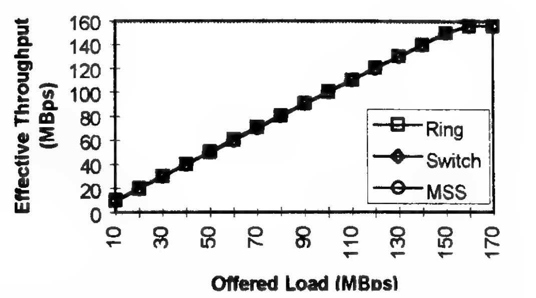

Figure 9: Streaming Scenario Throughput Results

Figure 9 shows that all three topologies can handle a single source saturating the network and all three saturate at the same rate (i.e. 160 MBps, which is 40 MBps less than the link data rate due to packet overhead). This chart does not show how much bandwidth is available after the network saturates. Since the ring topology shares bandwidth, very little bandwidth is available with a single high-load source. Both of the switch systems still have full bandwidth available on ringlets 2 and 3. The packet switch system has half of the internal fabric bandwidth remaining while the MSS has the full internal fabric bandwidth remaining.

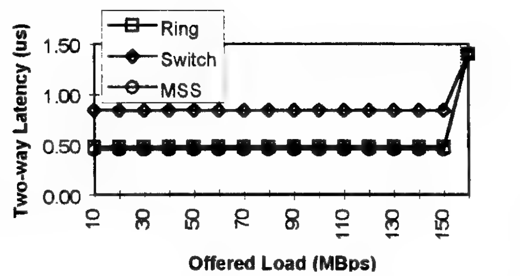

Figure 10: Streaming Scenario Latency Results

Figure 10 shows the latency for the streaming-load scenario. The packet switch system has a fundamentally higher latency than both the ring and MSS systems. This is the routing delay. Both the MSS and ring avoid any packet switching and therefore enjoy a lower minimum latency by approximately 0.4 μs. The MSS has a slightly lower latency than the ring due to the configuration. The number shown is the two-way latency of packets that were actually received. In the overloading case, latency is infinite since some packets will never reach their destinations so an appropriate number was chosen for display purposes.

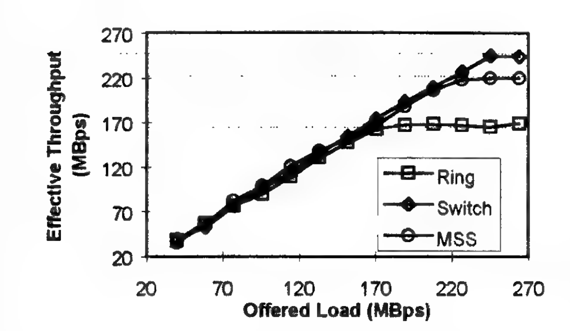

Figure 11: Random Scenario Throughput Results

Figure 11 shows the throughput of the random load scenario. This scenario shows the benefit of using a switched topology. Notice how the saturation bandwidth of both switched systems is higher than the ring which saturates at 166 MBps. The MSS, which has nodes 1 and 4 circuit switched onto the same ringlet, has a higher bandwidth than the ring due to its packet switch fabric but has a smaller throughput than the switched system due to the circuit-switched ringlet. Here, approximately half of the load uses the ring while half uses the packet switching (due to uniform distribution of destinations). Hence the performance of the MSS system is about halfway between the packet switched system and the ring system.

Figure 12 shows the latency for the random destination loading scenario. A distinction between the three systems can be seen here. Again, the performance of the MSS system is approximately halfway between the ring system and the packet-switched system. The packet-switched network has the lowest average latency for the random destination case. This occurs due to the sharing of bandwidth on the ring system as well as the ringlet in the MSS system.

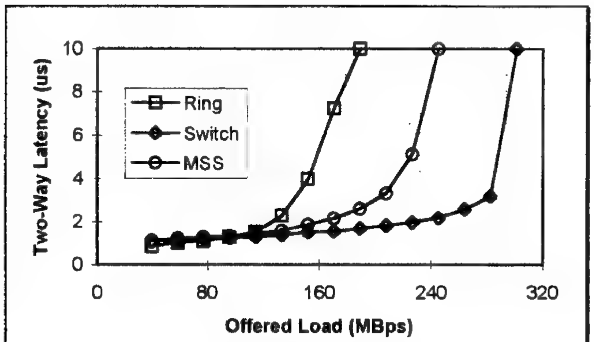

Figure 12: Random Scenario Latency Results

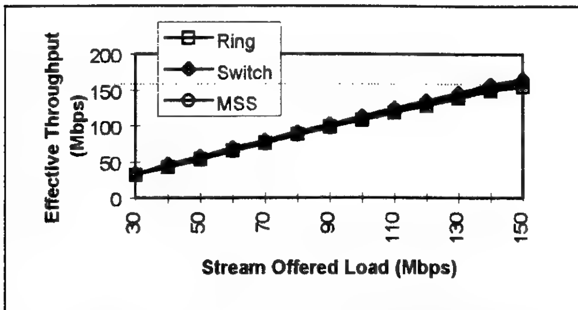

Figure 13: Mixed Scenario Throughput Results

Figure 13 shows the mixed load throughput results. Again, all three systems are able to saturate the network at the streaming load limit of 150 MBps. Recall that the mixed load is composed of the streaming load from node 1 and the random destination load that is 1/10th the streaming load (i.e. nodes 2,3, and 4 transmit at 1/30th the rate as node 1).

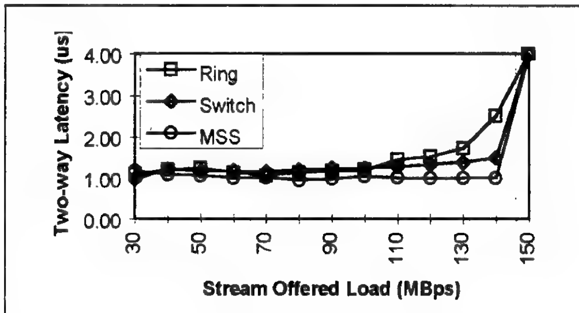

Figure 14: Mixed Load Latency Results

Figure 14 shows the latency of the mixed load scenario. Here, only two-way latency of the random destination packets for comparison with the random destination test. Under the mixed load scenario, the MSS system maintains the lowest average latency for the random destination packets while also having throughput that is as equally high as the other topologies.

Conclusions

This paper presented the design, modeling, and simulation of a novel switching technique for next generation avionics data networks. The multiservice switch offers two switching mechanisms to gain the performance and fault-tolerance benefits of a packet switch while simultaneously offering the low latency of a ring-based topology.

The performance improvements of the multiservice switch will allow system designers to reduce the packet switch speed requirements to attain the same level of performance for streaming loads. By reducing the speed of the packet switch, power and cost are reduced. The multiservice switch also shows equal if not better performance than conventional switches and topologies for mixed offered loads, which can be expected in an avionics data network.

Future Research

Future work on the multiservice switch will complete the prototype switch in both hardware and software. The prototype switch still requires control software to be written and some

hardware debugging. The simulator will be expanded to handle actual, rather than statistical, offered loads and to include more efficient switching mechanisms. The simulator will also be expanded to simulate the actions necessary for a run-time crossbar reconfiguration.

Acknowledgments

We would like to thank the Office of Naval Research for their support of this research as well as Michael Miars and Robert Todd of the High-performance Computing and Simulation Research Lab for their technical assistance.

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Simulation of a cell switched network for the control of a switch matrix in a high-speed avionics network

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1 ABSTRACT

This paper describes the research and experiments carried out by the National Aerospace Laboratory (NLR) in the field of high-speed interconnection systems for modular avionics. The research has been carried out in the EUCLID/RTP4.1-framework.

The avionics network that was modelled and simulated was an optical switch matrix under control of a cell switched network. The optical switch matrix offers the avionics system circuit-switched, uni-directional, point-to-point connections. A bandwidth of 2 Gbps is projected. The main purpose of the matrix is to connect sensors producing high data rates, such as an attack radar in fighter aircraft, with the core avionics processing cluster.

The cell switched network - in this case Asynchronous Transfer Mode (ATM) - controls the optical switch matrix and provides data transfer at lower data rates, file transfer, and status messages. The simulation model operated ATM at 149 and 622 Mbps.

The primary objective of our research was to assess ATM as a data link layer for a control and message network in an avionics data network. The computer-based tool to model the network was SES/Workbench.

2 ABBREVIATIONS

AAL	ATM Adaptation Layer
ABR	Available Bit Rate
ATM	Asynchronous Transfer Mode
B	Byte
B-ISDN	Broadband ISDN
CBR	Constant Bit Rate
CCITT	Consultative Committee for International Telegraphy and Telephony
CMN	Control and Message Network
DMA	Direct Memory Access/Addressing
EO	Electro-Optical
EUCLID	European Co-operation for Long term In Defence
Gbps	Giga bits per second
Hz	Hertz
ISDN	Integrated Services Digital Network
ITU-T	International Telecommunications Union, Telecom Standards Sector
kB	kilo Byte
LAN	Local Area Network
LCE	Link Control Element
Mbps	Mega bits per second
NLR	National Aerospace Laboratory
OSM	Optical Switch Matrix
PVC	Permanent Virtual Circuit
QoS	Quality of Service
RF	Radio Frequency
RISC	Reduced Instruction Set Chip
RTP	Research and Technology Programme
SCI	Scaleable Coherent Interface
SDH	Synchronous Digital Hierarchy
SES	Scientific & Engineering Software Inc.
STM	Synchronous Transfer Module
VBR	Variable Bit Rate
VC	Virtual Circuit
WAN	Wide-Area Network
WEAG	Western European Armament Group

3 INTRODUCTION

This paper describes the experiments and the results of research in the field of high-speed interconnection systems for modular avionics. This research has been carried out in the framework of EUCLID RTP 4.1.

3.1 Project background

The European Co-operation for Long term In Defence (EUCLID) Research and Technology Programme 4.1 "Modular Avionics Harmonisation Study" identified and researched the technologies available in Europe for the development of future avionics systems architectures. The programme was a joint effort of 27 companies in 6 European nations: France, Germany, United Kingdom, Spain, Italy, and the Netherlands. The consortium consisted of most European airframe manufacturers and equipment suppliers. EUCLID is a programme of the Western European Armament Group (WEAG).

The in-service time frame of the envisioned avionics systems was 2005-2010. The target programme can either be a retrofit of an existing aircraft or the development of a new aircraft. The types of activities in the programme involved definitions, specifications, surveys, simulations, and laboratory demonstrations.

The areas in which the National Aerospace Laboratory (NLR) was involved covered the following topics:

- high-speed interconnection systems;
- digital signal processing;
- fault-tolerance;
- component and rack cooling;
- system development tools.

Paper presented at the AGARD MSP Symposium on "Advanced Architectures for Aerospace Mission Systems", held in Istanbul, Turkey, 14-17 October 1996, and published in CP-581.

This paper focuses on our activities in the field of high-speed interconnection systems, the modelling and simulation thereof in particular.

3.2 Modular avionics architecture

The avionics architecture defined in the programme formed the basis for the simulation model. The core avionics architecture consists of ten functional areas and a unified data network interconnecting the functional areas. The ten functional areas are vehicle control, crew interface control, mission control, systems control, data base control, RF, EO, image analysis, image generator, and acoustics. Each functional area hosts a group of related functions to optimise the traffic across the network. Reference 1 describes in detail the rationale for the division of the core avionics into functional areas.

The following modules are the building blocks for the functional areas: data processing, signal processing, image processing, graphics processing, and memory modules. With the continuous increase in performance of processing devices, it is likely that eventually all processing takes place on generic processing modules.

Table 1 on page 16-8 shows the expected data traffic categories and their characteristics (Ref. 2). These categories and characteristics formed the basis for the workload for the simulations.

Analysis of the data traffic shows that the avionics network shall support three basic types of transmissions:
1. sustained, large amounts of data;
2. bursty, medium sized amounts;
3. short, but time critical messages.

To be able to service this variety of transmission types, a dual network approach was chosen. The dual network is called the 'Matrix Switched Network' (MSN). The MSN provides:
- a connection-oriented data transfer network for sustained, large amounts of data, typically originating from sensors;
- a control and message network to control access to the data transfer network and to facilitate transmission of bursty, medium sized amounts of data.

For the control and message network, the following protocols have been evaluated: 1553, FDDI, ATM, and SCI. ATM came out as most promising candidate, closely followed by SCI.

Because of the limited amount of resources we were able to model one type of protocol. For several reasons we decided to go for ATM:
- ATM came out of the evaluation as most suitable;
- ATM-technology is available on the market;
- there are several commercial as well as academic models available.

3.3 Objectives of the modelling and simulation

Our research involved the modelling and simulation of a typical functional area with the following three objectives:

1. Development of a model of the core avionics architecture defined in the programme.
2. Performance modelling of the avionics architecture model.
3. Assessment of ATM as data link layer for a control and message network for an avionics data network.

4 DESCRIPTION OF THE NETWORK MODEL

Before explaining how an ATM network can be used as a data link layer for a control and message network, an introduction to ATM networks will be given in section 4.1. Section 4.2 explains how an ATM network can be used as a basis for the control and message network. Section 4.3 describes the limitations of the model. Section 4.4 describes the simulation tool SES/Workbench briefly.

4.1 Introduction to ATM

In the mid-1980s when the ISDN standard was being developed, the CCITT began working on the successor of ISDN; it was acknowledged that ISDN would not offer enough bandwidth in the future. This successor is known as Broadband ISDN (B-ISDN). One key objective was to develop a technology that would allow for efficient transport of all kinds of traffic (bursty and isochronous). Further, the new technology should support future speeds of several Gigabits per second (Gbps). In 1988 the CCITT decided to base the development of B-ISDN on ATM which was formalised in the late 1980s. B-ISDN became one of the services that can use ATM technology.

ATM is a relatively new method to transport information. Two classical ways of transporting information are:
- Circuit switching: requires a circuit to be established prior to transport of data. Resources in the network stay reserved until the connection is torn down. Circuit switching is well suited for isochronous traffic. ISDN and the classical telephone network are examples of the use of circuit switching.
- Packet switching: suitable for bursty data transmission and unsuitable for isochronous applications. It is more efficient than circuit switching, because network resources are only used when traffic is present. Packet switching is used in LAN environments.

ATM is a cell switching technique. Cells are small, fixed-length packets of 53 Bytes that are switched to their destination by the hardware in network nodes (ATM switches). Cells can carry data from arbitrary applications (isochronous as well as bursty). ATM systems are connected to ATM switches by a dedicated link; there is no shared medium like in LANs. This means that distinct pairs of ATM systems can communicate at full wire speed with each other (if the switch has enough switching capacity). A switch can be equipped with different types (speeds) of ATM ports; this way a server on ATM can have a faster connection to the ATM network than its clients.
Before data can be transported, a Virtual Circuit (VC) has to be established between the two end-points that wish to communicate (ATM is connection-oriented). An application can negotiate a QoS required for its VC. An ATM system

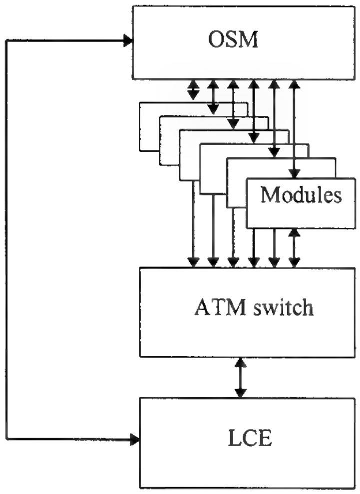

Figure 1 ATM as a control and message network

typically may use up to several thousands of Virtual Circuits simultaneously to different other ATM systems.

ATM supports four classes of traffic. Ordered in a decreasing priority the traffic classes are:

- Class A Constant Bit Rate (CBR), connection-oriented, synchronous traffic (uncompressed voice or video)
- Class B Variable Bit Rate (VBR), connection-oriented, synchronous traffic (compressed voice or video)
- Class C Variable Bit Rate (VBR), connection-oriented, asynchronous traffic (X.25, Frame Relay)
- Class D Available Bit Rate (ABR), connectionless, packet data (LAN traffic)

ATM is scaleable regarding both bandwidth and topology. Speeds are supported from 2 Megabits up to several Gigabits per second. ATM is often run over a physical layer consisting of one of the standards from the SDH hierarchy of optical

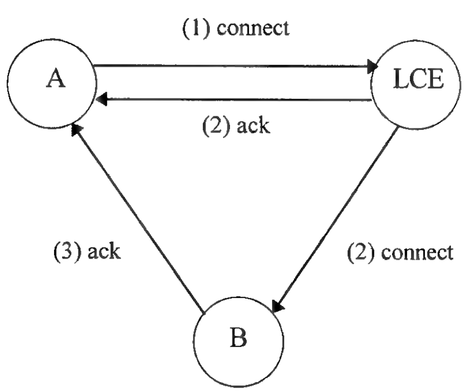

Figure 2 OSM-command Protocol

standards. The hierarchy ranges from STM-1 (155.52 Mbps) up to STM-16 (2.4 Gbps) while even faster standards are being developed.

ATM is suitable in LAN as well as in WAN environments. LAN and WAN connections differ regarding available bandwidth. That is why congestion and flow control are important issues in large ATM networks. The ATM Forum and the ITU-T (former CCITT) are currently working on standards to address these issues.

4.2 The model and its traffic

Figure 1 shows schematically how an ATM network can be used as the control and message network for the OSM.

The functional area that is modelled contains 6 modules that are all connected to both the OSM network via optical links and the CMN network (in this case implemented by an ATM network) via an ATM network interface to which an optical or electric link is attached. The OSM controller (LCE) is also connected to the CMN network.

Note that in this set-up, modules can not only communicate with the LCE, but also directly with each other by using a direct ATM virtual circuit between them without bothering the LCE.

Four kinds of traffic will be simulated in the model. These will be explained in the following sections.

4.2.1 Commands between modules and LCE

Each module can issue commands to the LCE to set up or tear down an OSM connection with other modules. The time between the transmission of the request and the moment at which transmission of data on the OSM connection can start, is called the link time. For the so-called unlink time (for tearing down a connection) a similar definition is valid. A driving requirement was that the (un)link time had to be less than 50 μs.

Several high-level protocols have been considered for accomplishing a reliable connection set-up. To minimise the link time, the protocol in Figure 2 was chosen. The protocol works the following way:

Suppose module A wants to set up an OSM connection with module B. Module A sends a connection request to the LCE. After receiving the request, the LCE checks whether module B is available for the requested connection. If not, the LCE sends a negative response to module A. If module B is available, the LCE sends a message to module B to inform about the OSM connection that is about to be activated. At the same time the LCE sends a positive response to module A and starts setting up the OSM connection. When module B receives the message from the LCE, it sends a (positive) acknowledgement to module A. When module A has received positive messages from both the LCE and module B, it may start transmitting data via the OSM connection.

For the simulation it has been assumed that 3 modules maintain the same, static OSM connection configuration (e.g. continuous high bandwidth demanding sensor processing). The remaining 3 modules are resources for which is competed. They randomly issue OSM-commands. These requests are exponentially distributed with a mean of 10 Hz. In a real network the mean OSM-command release rate is probably lower than 10 Hz. Because the link time of an OSM-connection is only worthwhile when relatively large amounts of data have to be transported. The message length is 25 B (fits into 1 ATM cell). Because of the need to minimise the link time, this traffic is assigned to the VBR traffic class and not to the low priority ABR class..

4.2.2 Status (synchronisation) traffic

It is assumed that each module periodically sends synchronisation or status data to the LCE for configuration management purposes. These are small messages (25 B) that fit into 1 ATM cell. They are generated with a triangular distribution with a mean of 1 ms (1000 Hz), a minimum of 0.8 ms and a maximum of 1.2 ms. This traffic is assigned to the ATM ABR traffic class.

4.2.3 Control/data traffic between modules

Applications use a higher layer protocol to synchronise their activities and to exchange information. This dynamic behaviour depends on the functionality and implementation of the modules. The dynamic behaviour is modelled by the following random parameters:

- message size;
- transmission interval;
- source module;
- destination module.

The size of the messages is uniformly distributed between 1 kB and 16 kB. The messages are generated with an exponential distribution with a mean of 5 ms (200 Hz). The source and destination modules are chosen according to a uniform distribution. This traffic uses the ATM ABR traffic class.

4.2.4 File transfer traffic between modules

Modules can exchange certain amounts of data for which it is not effective to request an OSM connection or when the desired OSM connection is unavailable. This data can be transported by means of a file transfer using the CMN. This results in a burst of maximum sized packets between two modules. The dynamic behaviour is modelled by the following random parameters:

- message burst size;
- source module;
- destination module.

The modules are chosen according to a uniform distribution, just like the file-size (between 64 kB and 192 kB). A file burst is generated every 0.1 s (10 Hz) and is assigned to the ATM ABR traffic class.

4.3 Abstractions and limitations of the model

This section describes limitations and abstractions of the model when compared to a possible real world implementation.

1. *Only Permanent VCs are used in the model.*
   The process of dynamically (on demand) setting up an SVC (Switched VC) can take milliseconds in a real ATM network. In the avionics system being modelled, such a delay is intolerable. Hence, it is assumed only PVCs (Permanent VC) are used. In a real implementation these can be set up automatically during system initialisation. As a consequence an ATM node can start transmitting data immediately; it is not necessary to set up a VC first.

2. *All links have the same bandwidth.*
   In an ATM network it is possible for a node that will receive/transmit more data than other nodes to have a higher capacity network-connection. Since in the model the traffic is fairly well distributed, an optimisation like this is not used. Simulations are run for ATM networks based on SDH STM-1 and SDH STM-4.

3. *Physical layer overhead not modelled properly.*
   In an ATM network based on SDH there is some overhead at the physical layer. On an STM-1 (155.52 Mbps) trunk every 27th cell is needed for that overhead limiting the available bandwidth to 149.76 Mbps. This is modelled assigning an overall available bandwidth of 149.76 Mbps to the ATM trunks; in stead of reserving every 27th cell. For STM-4 (622.08 Mbps) every 108th cell is not available, resulting in an available bandwidth of 616.32 Mbps.

4. *ATM interface processing overhead not modelled.*
   Of course, some processing needs to be performed at an ATM interface. ATM Adaptation Layer (AAL) headers/trailers must be added or removed. Packets of data have to be segmented/reassembled to/from cells. In state-of-the-art ATM adapters dedicated hardware is used to obtain a minimum latency (64 bit RISC processors, DMA, etc.). Data is transferred from/to the host memory while the cells of a packet are being transmitted/received to/from the ATM network. Latency introduced by a carefully designed ATM adapter is small when compared to the total latency of transferring a message through the ATM network.

5. *Higher layer protocols are not modelled.*
   The objective of the simulation was to focus on the ATM level of the CMN. Because of this, no higher layer protocols have been modelled. As a consequence no higher layer protocol headers have been taken into account when decreasing the maximum packet size during consecutive simulation

runs. As another, more serious consequence, no flow control is available. This means that all data for a file transfer enters the ATM-interface of a module as maximum-sized packets simultaneously.

6. *VC and their QoS parameters are not modelled.* In a real ATM network all data offered to an ATM network interface must be transmitted on a pre-established VC while respecting the QoS parameters that were agreed upon during the VC set-up ('traffic shaping'). The ATM model did not have options to specify other QoS parameters than the ATM traffic class. All data offered to an ATM network interface is transmitted as fast as possible (at the speed of the trunk connected to it). This is slightly worse than in the real world and increases the probability of cell loss in the switch.

7. *Packet transmission is considered un-interruptable.* It is desirable that the transmission of a (possibly large) low priority packet (e.g. ABR) is interrupted because a higher priority message (e.g. VBR) is offered for transmission to the ATM interface. Depending on the implementation of an ATM adapter and whether (and in what way) it enforces traffic shaping; this may be possible in a real ATM adapter. It is not included in the model. As a result the latency of high priority messages depends on the maximum packet size for lower priority messages.

4.4 Short description of the simulation environment

SES/Workbench is a graphically oriented general-purpose simulation language that contains features for modelling computer systems and communication networks. The graphical interface allows users to build and represent designs pictorially. The major building blocks are:

- Nodes
- Arcs
- Transactions

There four basic types of nodes:

<u>Resource management nodes</u>
Resource management nodes create, allocate and release the resources used by transactions. The resources may be processors, memory, communication links, busses and system processes.

<u>Transaction flow control nodes</u>
Transaction flow control nodes create, destroy, and alter flow of transactions through the system.

<u>Sub-model management nodes</u>
Sub-model management nodes allow a model to be developed and specified as a hierarchical collection of sub-models.

<u>Miscellaneous nodes</u>
Such as, user-defined nodes.

A collection of building blocks represents system components, processors, resources, transaction flows, and others. To build a model one defines a transaction that corresponds to a message. After that, a directed graph consisting of nodes and arcs is created. This is done by placing icons on the display that can be connected by arcs. The arcs and nodes describe how transactions flow through the model. In this way it is easy to create and view complex models.

SES/Workbench provides real-time animation that displays transactions flowing through the model and shows events that occur at nodes. Simulation results can be displayed in both numerical and graphical formats, either during the simulation or after it has been completed.

Several statistical functions, built-in probability density functions, and queuing disciplines are available.

5 EXPERIMENTS

5.1 Measurements

For the experiments the following statistics were measured:

- mean ATM-utilisation for:
  - network interfaces/links;
  - the ATM-switch;
- ATM-switch lost-cells;
- mean OSM-command response-time (including acknowledgements);
- mean status-message response-time (including acknowledgements);
- mean file-burst response-time (including acknowledgements).

5.2 Parameters

To investigate the model, the following parameters were varied:

• ATM-bandwidth	149 Mbps, 616 Mbps
• Workload	nominal, high (5 times nominal)
• Maximum packet-size	100%, 40%, 12.5%, 6.25% of control/data traffic and file-burst maximum packet-size

ATM-bandwidth and workload parameters were used to vary the traffic and stress of the ATM-network. The nominal workload described in section 4.2 results in a mean control and data traffic load of 13.67 Mbps and a mean file-burst load of 10 Mbps. The high workload approximately produces 5 times more traffic than the nominal workload: a mean control/data traffic load of 68.36 Mbps and a mean file-burst load of 50 Mbps. The high load control/data traffic is created by increasing the release-rate. The distribution in time of the extra packets is uniformly. The high load file-burst is created by increasing the range, from which the size of the file-burst is uniformly chosen, from [64 kB, 192 kB] to [320 kB, 960 kB]. The resulting extra file-burst traffic enters the network simultaneously.

As explained in sections 4.2 and 4.3, the larger the allowed packet-sizes, the higher the latencies of messages can become. For this reason, the maximum packet-size is varied during the experiments. For file-burst messages a smaller packet-size will result in more (but smaller) packets being generated simultaneously. The model does not include the effect of additional overhead needed to reassemble messages from multiple smaller packets. The OSM-commands and status-messages are not varied. As described in section 0 and 4.2.2 they always occupy 1 ATM cell.

5.3 Experiments

The following groups of experiments will be described:

- Reference experiments with single messages;
- experiments with an ATM-bandwidth of 149 Mbps during nominal operation;
- experiments with an ATM-bandwidth of 616 during nominal operation and operation under high loads.

All results are mean values over the complete simulation period and times are reported in μs.

5.3.1 Reference experiments

The response-times of an OSM-command message, a single-cell status-message and file-burst messages were determined, while no other messages were in the network. Note that all measured response-times include the latencies of acknowledgements being sent back to the source of the original messages. The service times in the involved modules and LCE were fixed to their mean service times (10 μs).

	149 Mbps ATM	616 Mbps ATM
Status-message	33.2	15.6
OSM-command	54.8	28.4
64 kB file-burst	3900	955
640 kB file-burst	42600	10400

The single-cell status-message response-time includes the following latencies:

- Four cell transmissions (message and acknowledgement) from the network interface to the ATM-switch and vice versa. This is the time needed to put bits of a cell on a link.
- Four link propagation-delays (2 for the message and 2 for the acknowledgement) from the source network interface to the ATM-switch and from the ATM-switch to the destination network interface. For the experiments all links had a length of 1 meter.
- Two switch delays (message and acknowledgement). This is the time to move the cell through the switch-fabric from the input port to the output port.
- One service time (10 μs) needed in the destination module to produce the acknowledgement.

The table shows that the 50 μs OSM (un)link-time requirement cannot be achieved with the 149 Mbps ATM-bandwidth.

5.3.2 149 Mbps experiment

Description:

OSM-command, status-message and file-burst mean response-times, during nominal load, 149 Mbps ATM, a 20 second simulated time and triangular distributed services times for modules and the LCE with a minimum of 5 μs, a mean of 10 μs and a maximum of 15 μs.

Parameters:

packet-size (in percentages).

Results:

Size	OSM-command	Status	File-burst
100	147.6	167.2	14678
40	81.4	125.4	9674
12.5	66.5	101.5	8408
6.25	59.1	89.9	8507

Figure 3 shows the measured response times of the OSM-commands and status messages with the ATM network opating at 149 Mbps and with a nominal workload.

Conclusions from the measurements:

- smaller packet sizes reduce the response-times;
- the improvement of the mean file-burst response-time with smaller packet-sizes is because of a decrease in packet-size of the control/data traffic. This decrease causes the control/data traffic load to be more uniformly distributed in the functional area (space) and in time;

The mean OSM-command response time during high load, 149 Mbps ATM with 100% packet size was 400 μs. (Because this result is far from the desired 50 μs, further experiments were concentrated on 616 Mbps ATM-bandwidth experiments.)

The following ATM-network statistics were measured:

Utilisation of:	Nominal load	High load
ATM switch	1.5%	6.2%
Module Net Interface	3.6%	15.5%
LCE link	1.8%	1.8%

The experiments showed that when occurrences of file-bursts overlap in time and space (to the same destination-module), cell-loss can occur even during nominal load. (In such a case the ATM-switch output buffer to the involved destination-module is easily congested.)

5.3.3 616 Mbps experiments

Description:

OSM-command, status-message and file-burst mean response-times, during nominal and high load, 616 Mbps ATM, a 20 second of simulated time and triangular distributed services times for modules and the LCE with a minimum of 5 μs, a mean of 10 μs and a maximum of 15 μs.

Parameters:

packet-size (in percentages);

load (nominal or high).

Results:

Nominal load:

Size	OSM-command	Status	File-burst
100	36.2	23.8	2863
40	29.0	20.5	2367
12.5	29.2	19.9	2069
6.25	28.5	19.5	2024

Figure 4 shows the measured response times of the OSM-commands and status messages with the ATM network opating at 616 Mbps and with a nominal workload.

High load:

Size	OSM-command	Status	File-burst
100	50.2	150.5	12018
40	39.9	91.9	9911
12.5	32.6	150.6	12482
6.25	30.7	101.5	11109

Figure 5 shows the measured response times of the OSM-commands and status messages with the ATM network opating at 149 Mbps and with a high workload.

Conclusions from the measurements:

- With the high load, 94% of the OSM-commands are processed within 50 μs. (This statistic is not shown in the tables).
- With the nominal load the packet size has only minor influence on the response-times, because packets that block the network interface of a sending module (or the ATM-switch) for packets that follow, are served 4 times faster in the ATM-network than during the 149 Mbps experiments;
- The irregular shape of the graph of the high load file-burst response-time may be caused by file bursts that overlap in time and/or space. One of the following scenarios might have occurred:
    1. Bursts overlap in time and are transmitted from the same module. Because all bursts have the same priority, the second burst is delayed until the first burst has been transmitted;
    2. Bursts overlap in time and are transmitted from different modules, but to the same module. This causes both extra delays and cell-loss in the ATM-switch. During the experiments with nominal load, almost no cell-loss occurred.

Because of the relatively short simulated time of 20 seconds an occurrence of one of these scenarios has a large impact on the shape of the graph. Inspection of the collected statistics showed that the experiments that were responsible for the peaks in the high load graphs suffered from severe cell-loss when compared to the other experiments in the same graph. This may indicate that scenario (2) is responsible.

- The irregular shape of the graph of the high load status-message experiments is similar to the shape of the high load file-burst experiments. The status-messages suffer from the file bursts the most, because status messages have the same priority as file bursts, while the OSM-commands have a higher priority.

The following ATM-network statistics were measured:

Utilization of:	Nominal load	High load
ATM switch	0.4%	1.5%
Module Net Interface	0.9%	4.0%
LCE link	0.4%	0.4%

6 CONCLUSIONS AND RECOMMENDATIONS

From the simulation experiments the following can be concluded.

1. During high load with a maximum packet-size of 64 kB, 94% of the OSM-commands (link or unlink commands) are processed within 50 μs when:
    - at least a 616 Mbps bandwidth is used for the ATM-links and network interfaces;
    - an ATM-switch is used with a 9.86112 Gbps aggregate bandwidth, with a typical switch fabric latency of about 5 μs;
    - the module and LCE service times approximate a triangular distribution with a minimum, maximum and mean of respectively 5 μs, 15 μs, and 10 μs;
    - OSM-commands have priority over other packets in the ATM network interface and other cells in the ATM-switch.

2. Because the status traffic introduces only minor workload (thus minor latency for lower priority messages) and it is important that status-messages have a low latency, it is recommended that these messages have a high ATM-priority like the OSM-commands.

3. It is recommended that both the ATM network interfaces and the ATM-switch have separate output-buffers for cells with different priorities to make the latency of high priority messages independent of the packet-size of lower priority messages.

4. Traffic-bursts such as simulated in the model should be suppressed or controlled to prevent:
    - that the network interface of a module is blocked for other traffic;
    - that the packets of a burst are transmitted one-after-the-other without gaps, causing severe load-peaks. For this purpose higher layer protocols could be used, that apply flow control, e.g. sliding-window mechanisms, and at the ATM-layer Virtual Circuits for each traffic-stream with properly configured QoS-parameters to enforce traffic shaping.

5. Because it is expected that the bandwidth of ATM-networks will be increased significantly in the near future and because in an ATM-network different types of data can be transferred with different QoS, it should be considered to transfer the high bandwidth data via the ATM-network as well. Because the OSM would no longer

be necessary, the complexity of the avionics network would be reduced significantly.

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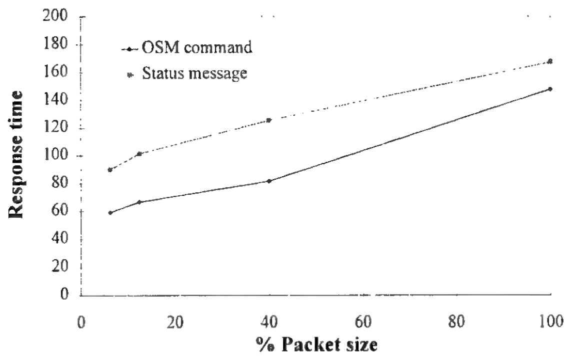

Figure 3 Measured response times with 149 Mbps ATM with nominal workload

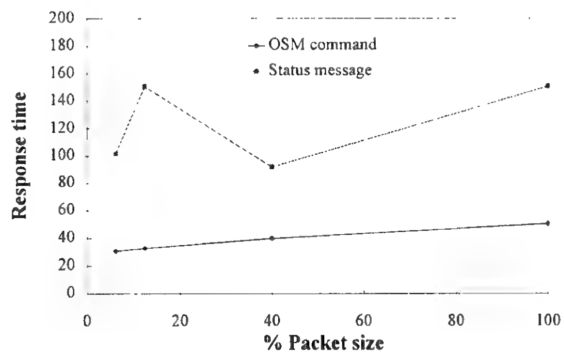

Figure 5 Measured response times with 616 Mbps ATM with high workload

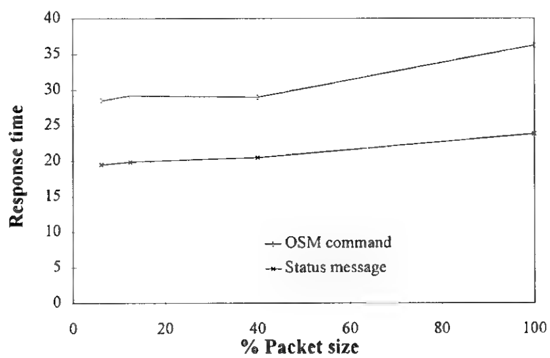

Figure 4 Measured response times with 616 Mbps ATM with nominal workload

Table 1 Data categories and characteristics

Parameter	Video	Fast sensor	Medium sensor	Slow sensor	Control/data	Sync	File transfer
Data rate - applications - frame length - rate	2 Gbps Video 25 Mbits 80 Hz	2 Gbps Radar 2 Mbits 1 kHz	750 Mbps Beam steer 64 kbits 10 kHz	250 Mbps E/O data 5 Mbits 50 Hz	< 1 Mbps Various 32 bits - 132 kbits 50 - 200 Hz	< 1 Mbps Various < 100 kbits 50 Hz - 1 kHz	< 1 Gbps Various 1 Mbit
Periodic/aperiodic	periodic	periodic	periodic	periodic	both	periodic	aperiodic
Persistence	10s of s	10s of s	10s of s	10s of s	10s of s	10s of s	message length
Latency - bit - frame	 10s of ms	 5 μs	 5 μs	 5 μs	 100 μs	 10 μs	 1 ms
Time tagging	no	yes	yes	yes	-	-	no
Topology	point/point	point/point	point/point	point/point	multipoint	multipoint	point/point
Delivery guarantee	Bit errors detected	Bit errors corrected	Bit errors corrected	Bit errors corrected	Frame acknowledgemt	Frame errors corrected	Frame acknowledgment

MULTIFUNCTIONAL RADIO SYSTEMS FOR MULTINATIONAL FORCES

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1. ABSTRACT

Modern technological and technical possibilities of multifunctional, fault-tolerant radio systems for armed forces operations are described.

With the availability of new technologies it appears technically feasible to adjust the nationally diverse radio signal formats in multinational operations and to exchange them internationally without compromising any security interests of the operating forces. The central technical parameters of the participating nations' radio functions need to be exchanged for this purpose.

However, such parameter exchange does not restrict the use of nationally defined waveforms. Due to present capabilities, the simultaneous use of radio functions on a national and multinational basis is possible for cooperating forces and, due to the expected benefits, ought to be recommended.

Command distribution via both national communication channels and multinational fast communication channels permits nationally supported multinational command structures. A unique way to achieve different national COMSEC codes will be derived from so-called c*) Codes. The c code can be transmitted via national and multinational protected channels without any loss of security.

Armed forces require a new, additional possibility of operating with multifunctional radio systems in missions with high security requirements for the communication equipments. During mission preparation, the ECCM measures for the communication systems are designed especially for the mission. Such radio waveforms tailored for a specific mission will result in greater protection compared with generally defined radio waveforms, which are partially known worldwide, without losing the possibility of cooperating with other participating forces, by using exchangeable waveforms for these communication links.

2. INTRODUCTION

The new, international doctrine assumes that the classical confrontation of East-West is brought to an end. This new perception forsters a new way of cooperation, where time and area play an important factor, and the purpose of the military power appears to be changed,

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sometimes to humanitarian aids objective. NATO and remaining CSCE states collaborate in new missions such as peace keeping and peace enforcing, and a regional conception is about to emerge. This new attitude requires a completely different understanding of interoperability and of communication for armed forces missions. Whereas, in the past, interoperability of weapon systems appeared to be required, the new doctrine emphasizes an improved communication interoperability. It is via communication that forces from different nations can be coordinated, and time-dependent coalitions for specific tasks can be achieved provided a political mandate is given.

Radio systems are used by the military for the following three purposes:

- communication,
- navigation,
- identification,

Common to these functions is the transport

- of information (with communication)
- of means (with navigation)
- of situation (with identification)

via a suitable structured radio waveform. The manipulation of radio waves determines the system architecture and its inherent characteristics.

New military equipment open the way, in association with the existing technical structures, that a multinational interoperability mission via support of adequate radio systems appears possible. However, at present, necessary procedures do not yet exist.

3. PRESENT TECHNOLOGY

Today's military radio systems contain many different radio tasks for communication, navigation and identification. Radio functions, like VHF/UHF, JTIDS/MIDS, GPS, NIS, and SATCOM are handled by an individual equipment often consisting of various LRUs. Without a built-in redundancy, failure of a single LRU can result in a failure of a radio function. In the future, individual radio functions need to be integrated as a modular system concept with software-controlled radio functions.

New technology for military radios will be based on an equipment architecture of a single radio in which all radio functions are determined by adequate software algorithms.

3.1 System Architecture

In principle, the new architecture for a Multirole Multifunctional Modular Radio (M3R) consists of the following five modules:

- Antenna System,
- Transmitter / Receiver,
- Pre-Signal Processor,
- Data Processor,
- Man-Machine Interface (MMI).

A suitable architecture for radio systems based on these modules is shown in the attached Figure 1.

3.2 Allocation of Functions

The main functions of a Multirole Multifunctional Modular Radio system are allocated to the above modules as follows:

3.2.1 Antenna System Module

The antenna system module comprises the following elements:

- Antenna switching
- Matching
- NEMP protection
- Transmit/receive switch

For tactical M3R, an antenna in a suitable frequency range of 30 to 88 MHz (HF), of 118 to 156 MHz (VHF) and 225 to 400 MHz (UHF) is required. In view of the different waveforms, antennas with omnidirectional pattern are preferably used.

3.2.2 Transmitter / Receiver Module

The Transmitter/Receiver(T/R) module has three functions:

- transmitting,
- receiving,
- synthesizing

for processing mainly analog signals.

The following four main parameters have to be changed in the new transmitter/receiver module to acchieve various radio waveforms necessary for communication interoperability:

- frequency range,
- filter bandwidths,
- modulation mode and
- hop rate.

3.2.2.1 Transmitter

The transmitter amplifies the modulated RF signal (supplied by frequency synthesizer) to the required transmitter power and applies the transmit signal to the antenna system.

The implementation of different waveforms in the transmitter does not only require different frequency ranges but also a waveform-specific implementation of the standardized time functions for transmitter keying in hopping mode (time constants: dwell rise time, dwell fall time, etc).

The transmitter comprises the following elements:

- RF amplifier and RF bandpass filter (e.g. for PSK mode)
- Amplitude modulator
- Power amplifier
- Harmonics filter
- Collocation filter
- Transmitter keying in frequency hopping mode

3.2.2.2 Receiver

The receiver converts the RF signal picked up by the antenna into an IF signal. The receiver comprises the following elements:

- Input filter
- Preamplification
- Multistage frequency conversion
- Multistage IF signal processing
- Generation of a digitized IF signal
- Automatic gain control (AGC)

3.2.2.3 Synthesizer

In transmission mode, the frequency synthesizer supplies the frequency-modulated RF signal to the transmitter, whereas in re-

ceive mode it supplies the conversion signal to the receiver.

The various radio waveforms differ in the synthesizer in the hop rate (transient times), frequency ranges, modulation methods and specific filtering of the baseband signal to be transmitted.

3.2.3 Pre-Signal Processor Module

The main task of the digital signal processor module is to demodulate the received signal and to process the demodulated signal for the data processing, i.e. amplitude- and time-regenerated data streams for further processing by the subsequent data processor are available at the output of the pre-signal processor for all waveforms.

The distribution of the functions between the "digital pre-signal processor" and the "data processor" may vary according to the waveform under observation. One of the criteria is the required or available computing power of the processor and another one the complex relationship between the regenerated baseband data and the waveform-specific TRANSEC algorithms.

3.2.4 Data Processor Module

The Data Processor Module comprises all functions required for successful interoperability of radio communication. These functions may include - among others - TRANSEC processing and time management. The digital processing functions are mainly implemented at the useful data rate (i.e. 16 kbit/s) and at the radio bit rate (i.e. 25 kbit/s).

The following functions are implemented in the data processor:

- Operating mode control
- Radio monitoring
- Call management
- Call acquisition
- Net management
- Time management
- Clock generation
- TRANSEC processing
- Frequency management
- Data transmission functions

3.2.5 Man-Machine Interface (MMI)

Within a given basic architecture, the MMI comprises all interfaces to the user. These include both the operator interfaces (manual control and load functions) and the communication interfaces (voice and data).

The functions of the MMI are hardly affected by a waveform switch if the useful data rates in speech mode are identical (e.g. CVSD with 16 kbit/s) and are in the same order in the data modes. Only the structures and the contents of the operating parameters (time, key, net number) will have waveform-specific characteristics.

The following interfaces will need to be implemented:

- digital interface to handset,
- digital interface to fill device,
- data interface

4. CONSEQUENCES OF PRESENT TECHNOLOGY

4.1 Radio Controllability

The presently used RF waveforms are characterized via 60 to 120 technical parameters im-

plemented within the above described modules. If interoperability is needed for missions, an exchange of radio parameters between the various armed forces will determine whether various radio sets in the different radios will cope with the required communication.

The new technological capabilities enable a fast change of radio function parameter in each functional block via software instructions. In recent years, all relevant radio parameters which influenced the waveforms were analyzed in Germany for each of the above described modules. These parameters uniquely characterize all known waveforms. Based on newest technology trends, there are approximately 500 qualitative parameters which characterize all current radio waveform. Recent data processor modules allow a predetermination and a continuous control of more than 500 well-defined radio parameters.

Figure 2 summarizes the allocation of the radio parameters and attaches so-called module functions and waveform parameters. Figure 3 lists some of those parameters and provides a short description of the relevant parameters. Figure 4 summarizes typical values for such parameters and provides information where the parameters might functionally be located.

4.2 Programmability of Radio System

The use of such multifunctional radios does not preclude their employment for strict national purposes.

Therefore, interoperability of radios is software-controlled and can be programmed into the data processor module of international partners' radios, provided an adequate data exchange will define actual parameters of the radio waveform required. Thus, secure multinational operations are ensured.

Furthermore, the programmability of all parameters for ECCM capabilities will improve the flexibility of communication equipment for different operations and improve the ECM resistance of the troops, based on the great variety of possibilities of different ECCM actions carried out during different time slots.

Modular radios in the different national forces provide the chance to exchange the essential radio waveform parameters, with other nations and with other services for special operations, and thus improve the technical performance of national communication systems.
For example, a software-controlled radio set (Figure 5) will define required functions. The radio functionality is achieved via

- the individual personality part which includes the SW object set (i.e. pre-defined SW pack-

ages), switch settings etc., and
- the physical characteristics inherent in the host equipment.

The advantages of software-controlled radios, namely
- multipurpose communication: increased communication capabilities can be applied in different networks
- access: communication access is provided in multinational environment
- short training cycle: the MMI can be identical with present radios

become obvious.
Such a radio system opens the way to a great number of user interfaces for military missions in view of formation of different radio waveforms.

4.3 Scheme for Interoperability

As shown in Figure 1, the control of the different waveforms is located in the RCCS in which the radio waveform parameters for a special waveform are stored. Such a storage can be organized in conjunction with c-coded parameter sets. For radio interoperability these c-coded parameters are determined by the nations.

These c-coded waveform parameters (international parameters) do not influence the parameter sets of nationally defined waveforms. Dependance of the c-coded parameters with non-c-coded parameters is impossible: both parameter types are strictly separated.

The c-coded waveform parameter can be exchanged by the multinational mission planning office, without the participating nations jeopardizing the security of their own national radio waveforms. The handling of the multinational c-code should multilaterally be agreed, however. These upcoming agreements include the definition of official channels for c-code exchange. The c-code exchange is the basis of mission interoperabilty of nations' armed forces.

4.4 Application of Multinational Radios

Many different RF waveforms exist worldwide today. A lot of them are also well-known worldwide. Special operations at the national as well as the international level may require a need to improve the security of RF waveforms. For operations with high security requirement (Electronic Counter Measures) the use of multifunctional radio systems opens the way for the design of special ECCM capability for a pre-defined mission.
The described military SW radio for interoperable use opens the way to increasing the security of the radio links dramatically for special missions or operations. Figure 6 shows the use of RF waveforms during the operation of an airplane with different functional priorities for the various radio waveforms.

In the case of using multifunctional radio equipment, it is possible to adapt the radio waveform in accordance to the flight

requirements, i.e. UHF radio waveform (Ground operation) and the JTIDS waveform (enroute operation).

During mission switching to a new waveform is extremely ECM-resistant and improves communication security.

4.5 Points of Core Agreement for interoperable use of multifunctional Radio Equipment

This technology of multifunctional radios provides technical means for mission interoperable radios of various services and nations.

Therefore, the nations need to bear in mind that in the long run

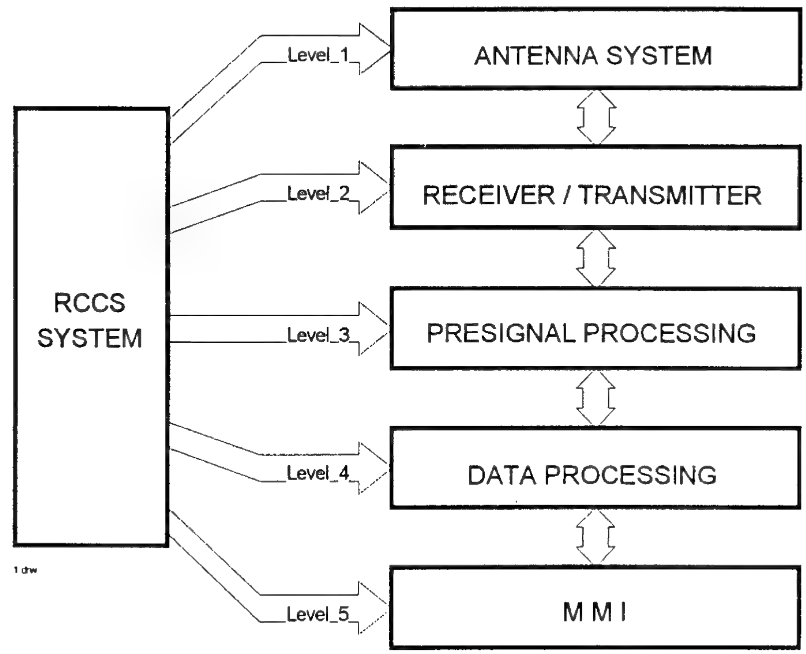
- only radio systems interoperable with or adaptable to the c-coded parameter requirement should be used,
- radio systems equivalent to the described modules should be integrated with mission avioncis,
- relevant parameters should be exchanged as early as possible,
- such radio systems should be integrated into aircraft operated during joint missions.

5. CONCLUSIONS

Technical possibilities for controllable radios, in combination with the added c-codes waveform parameters, will close the deficiency of unavailable interoperable open radio systems for secure multinational missions. Further actions by national authorities are required to improve the current situation by defining the necessary international communication procedures.

List of Abbreviations:

AGC	Automatic Gain Control
COMSEC	Communication Security
CPFSK	Continuous Phase Frequency Shift Keying
CSCE	Conference on Security and Co-operation in Europe
CVSD	Continous various Slope Delta Modulation
ECCM	Electronic Counter Counter Measure
FM	Frequency Modulation
GPS	Global Positioning System
HW	Hardware
IF	Intermediate frequency
JTIDS	Joint Tactical Information Distribution System
LRU	Line Replaceable Unit
M3R	Multimode Multifunctional Modular Radio
MIDS	Multifunctional Information Distribution System
MMI	Man-Machine Interface
NATO	North Atlantic Treaty Organisation
NEMP	Nuclear Electromagnetic Pulse
NIS	NATO Identification System
RCCS	Radio control configuration system
RF	Radio Frequency
SATCOM	Satellite Communication
TRANSEC	Transmission Security
UHF	Ultra High Frequency
VHF	Very High Frequency



RCCS = RADIO CONTROL CONFIGURATION SYSTEM

MMI = MAN MACHINE INTERFACE

Figure 1 : Multirole, Multifunction Modular Radio Architecture

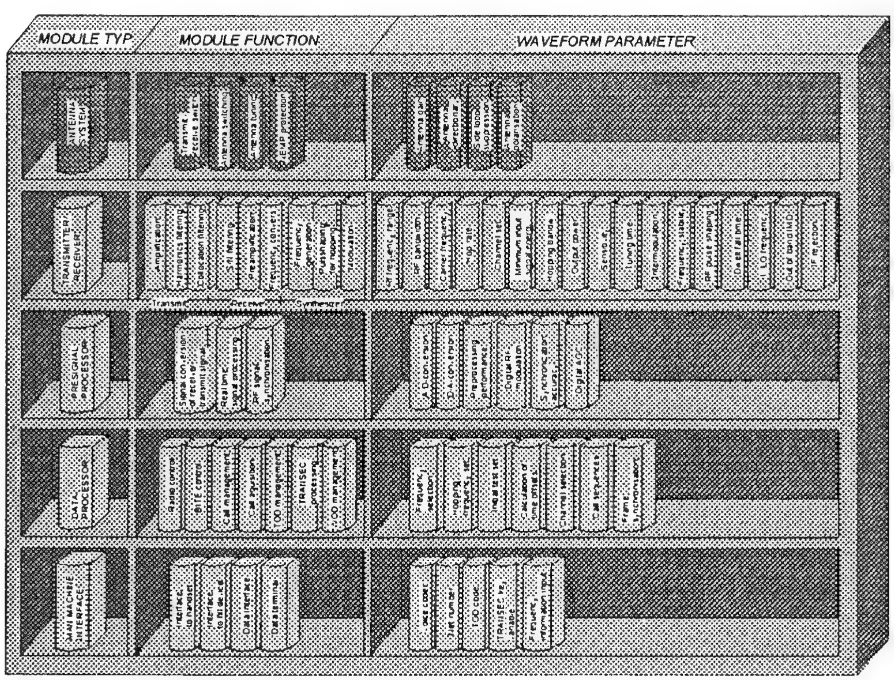


Figure 2 : Allocation of function

Line	Name of Parameter	Description
14	Audio Analog / Digital Conversion Clock	This parameter specifies the sampling period of the audio analog-to-digital converter output.
15	Audio Analog / Digital Conversion Resolution	This parameter corresponds to the number of quantisation levels applied by an audio analog-to-digital converter to transform the received analogous signal value assigned to one sample period.
16	Audio Center Frequency	Some HF data link systems modulate a carrier centered at RF + x Hz where RF is the HF frequency to be used and x the Audio Center Frequency.
17	Audio Input Level	This parameter defines the standard input level at the analogue voice interface (e.g. level of microphone).
18	Audio Output Frequency Response	Set of parameters to define the frequency response of the output signal at the voice interface (e.g. characteristics ans cut-off frequencies of applied filter).
19	Audio Output Level	This parameter defines the standard output level at the analogue voice interface.
20	Automatic Link Establishment	The capability of a radio station to make contact, or initiate a circuit, between itself and another specified radio station, without operator assistance and usually under processor control. Several techniques and protocols for the Automatic Link Establishment are in use to implement this feature.
21	Back Up	Space of memories required in a software controlled radio for fixing the functionality of the different equipment parts to realize a special waveform.
22	Baseband Pulse Response	The Baseband Pulse Response is used to describe the time continuous modulation signal of a digitally modulated waveform. It is usually defined as the pulse response of a linear filter, which receives the baseband symbols at its input and transmits the modulation signal at its output.

Figure 3 : Short description of selected radio parameter (some examples)

Line	Name of Parameter	ISO/OSI	Antenna	TX/RX	Preprop	Dataprop	MMI	Un-classified Value Radio 1	Un-classified Value Radio 2
14	Audio Analog / Digital Conversion Clock	1					X	16 kHz	ECCM : 14,4 kHz, AKW and HW Krypto : 16 kHz
15	Audio Analog / Digital Conversion Resolution	1					X	1 bit	1 bit
16	Audio Center Frequency	1			X				
17	Audio Input Level	3					X	0,25 Vrms @ 150 Ohm	250 mV @ 150 Ohm
18	Audio Output Frequency Response	3					X	+/- 3 dB ripple; 300-3500 Hz	0,3 ... 3,0 kHz
19	Audio Output Level	3					X	2,75 Vrms @ 150 Ohm	50 mW @ 600 Ohm, 1 W @ 50 Ohm
20	Automatic Link Establishment	2				X			
21	Back Up	2				X			1 Mbit
22	Baseband Pulse Response	1		X.	X			Continuous phase	Raised cosine

Figure 4 : Allocations of selected parameter within modules and realization

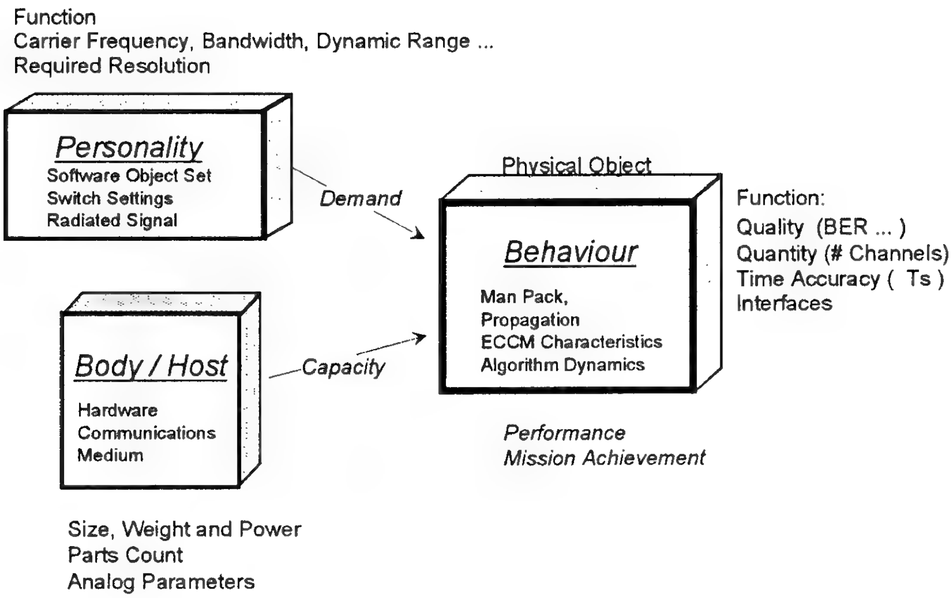
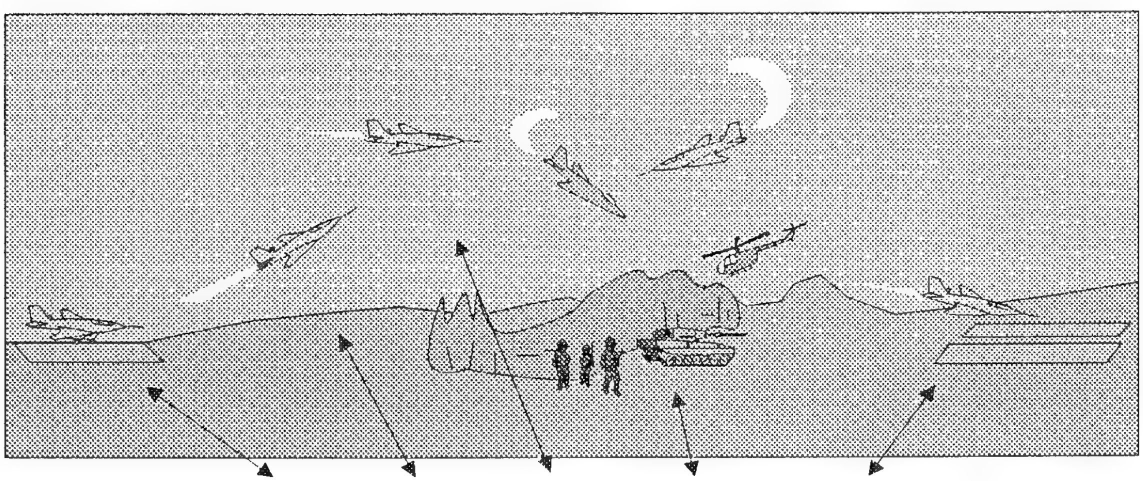


Figure 5 : Radio Functionality Splitting



	Ground Operation	Take Off	Enroute	Combat	Approach / Landing
HF	---	---	*	*	---
VHF	***	***	---	---	***
UHF	**	***	***	***	**
JTIDS	---	---	***	***	---
MLS / DME-P	---	---	---	---	***
Radar Alt.	*	**	**	***	**
GPS	*	***	***	***	**
NIS	*	*	***	***	**
SATCOM	**	*	***		**

--- = no use
* = low priority
** = medium priorit
*** = high priority

Figure 6 : Functional priorities of RF-use during flight mission

RAPID TARGETING AND REAL-TIME RESPONSE:
The Critical Links for Effective Use of Combined Intelligence Products in Combat Operations

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SUMMARY
A variety of advanced technology projects have demonstrated the key components required to provide rapid targeting for a real-time response. Forward Hunter (led by NAWCWPNS) and Goldpan (led by the Air Force's Aeronautical Systems Center) are examples of Real-Time Information into the Cockpit/Offboard Targeting (RTIC/OT) demonstrations. These programs have shown the value of providing real-time mission updates (based on national offboard signals and imagery intelligence) to shooters pursuing time-critical targets. All these programs employed national exploitation systems and source material products to show that RTIC/OT can increase mission effectiveness, enhance survivability, and increase operational flexibility against time-critical fixed and mobile targets. Each demonstration has focused on different aspects of critical offboard targeting technologies, such as multisource national/ theater intelligence fusion, rapid targeting, near-real-time mission replanning, data dissemination, and onboard processing.

ACRONYMS

ACC	Air Combat Command
ACI	Advanced Capabilites Initiative
AN/AWW-13	U.S. Navy advanced data-link (ADL) pod
AN/AXQ-14	USAF data-link pod
AOC	Air Operations Center
ASARS	advanced synthetic aperture radar system
ASC	Aeronautical Systems Center
ATIMS	Airborne Tactical Information Management System
ATO	air tasking order
CVIC	CV (aircraft carrier) Intelligence Center
DBS	Direct Broadcast Service
ESAI	expanded situational awareness insertion
EUCOM	U.S. European Command
GBU-15	modular guided glide bomb family
GPS	global positioning system
IMINT	imagery intelligence
JDAM	joint direct attact munition
JSOW	joint standoff weapon
JSTARS	Joint Surveillance Target Attact Radar System
JTIDS	Joint Tactical Information Distribution System
JWID	Joint Warrior Interoperability Demonstration
MINT	multisource intelligence
MISST	Mobile Intelligence Strike Support Team (NAWCWSPNS)
MNS	Mission Need Statement
NAVAIR	Naval Air Systems Command
NAWCWPNS	Naval Air Warfare Center Weapons Division
NIS	national input segment (JSIPS)
NRL	Naval Research Laboratory
NSAWC	Naval Strike and Air Warfare Center
OBTEX	offboard targeting experiments
ONR	Office of Naval Research
RITA	rapid imagery transmission to aircraft
RJ	rivet joint
RTIC/OT	real-time information to the cockpit/ offboard targeting
RTR	real-time retargeting
RTT	real-time tasking
SAR	synthetic aperture radar (generic)
SATCOM	satellite communications
SIGINT	signals intelligence
STS	sensor-to-shooter
SWC	Space Warfare Center
TAMPS	Tactical Aircraft Mission Planning System
TARPS	Tactical Air Reconnaissance Pod System (F-14)
TBM	theater ballistic missile
TENCAP	tactical exploitation of national capabilities
TLAM	Tomahawk Land Attack Missile (BGM-109)
TMD-HG	theater missile defense - high gear
TRAP	tactical related applications broadcast
UAV	unmanned air vehicle

OBJECTIVE
While the goal of this paper is to present an historical perspective of RTIC/OT technologies, NAWCWPNS primary focus is to facilitate the transition of RTIC/OT technologies and converge toward

- Establishing a near-term RTIC/OT concept of operations (CONOPS) based on existing systems and technologies and developing a migration path to systems and advanced capabilities slated to be available within a 2005 to 2010 time frame.
- Refining operational prototypes used in ongoing RTIC/OT demonstrations.
- Preparing near-term, mid-term, and long-term technology transition and deployment plans focused on Navy operations and joint service participation.

PROBLEM
What are the warfighters' needs? Precision attack of fixed and rapidly relocatable targets with brief attack windows (e.g., Scud missile launchers in Iraq, camouflaged tanks and artillery in Bosnia, and antiship surface-to-surface cruise missile (SSCM) launchers in the case of amphibious missions) is one of the primary areas in which improved capabilities are needed. National and theater intelligence assets, especially imagery-capable systems, must now detect and localize the target and threats for aircraft in a more timely manner to address the dynamic battlefield (Fig 1).

Current tactical strike aircraft weapon inventories and rules of engagement dictate that the weapon platform make a direct attack and acquire the target with a high-resolution sensor at close range. For the aircraft to survive in a hostile threat environment, minimal exposure time—"one pass, one kill"—and situation awareness (i.e., where are the

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nearby threats?) are the keys to survival. Currently, accurate target coordinates and funnel navigation imagery (Fig 2) meet the needs of man-in-the-loop attacks with the present weapon inventory (primarily, laser-guided bombs). Future global positioning system (GPS) or seeker-based bomb-on-coordinate standoff precision-guided weapons (IOC beyond the year 2000) will require more accurate target coordinates and drive advances in digital data links and onboard data processing.

Examination of the Navy's littoral strike mission and the Marine Corps' Operational Maneuver From the Sea reveals that the carrier and amphibious assault ships responsible for providing targeting and command/control are not outfitted with the intelligence feeds, exploitation systems, communications links, and theater battle management (TBM) capabilities required for RTIC/OT. The same is true for Air Force Close Air Support, Deep Strike, and Global Reach capabilities.

Furthermore, Fleet involvement in establishing the operational flow from sensor-to-shooter (STS) and in developing tactics is essential to field an operational RTIC/OT capability. Gaining an operational understanding of national intelligence capabilities is a fundamental skill required to produce effective products in time-critical combat situations.

OPERATIONAL CONCEPT

Fig 3 illustrates our advanced RTIC/OT operational concept for deployed sea-based applications. Our concept is focused on the capability to reduce mission planning time, as well as process RTIC/OT updates during the mission execution phase in response to dynamic battlefield conditions. This concept was derived from our baseline architecture used to support current demonstrations and exercises, and is accomplished by using common electronic digital target folders and exploitation tools across the system. Use of the following key elements are shown in Fig 4.

•**Multisource Feeds.** Real-time receipt of national signals intelligence (SIGINT) data (e.g., TRAP), as well as the capability to request collection of or access to existing archive imagery intelligence databases via a National Input Segment or Custom Product network (i.e., NIS, CPNet reachback). This access includes the capability to import theater-level multisource intelligence data (e.g., U-2, JSTARS, RJ, UAVs) and rapidly fuse with national products

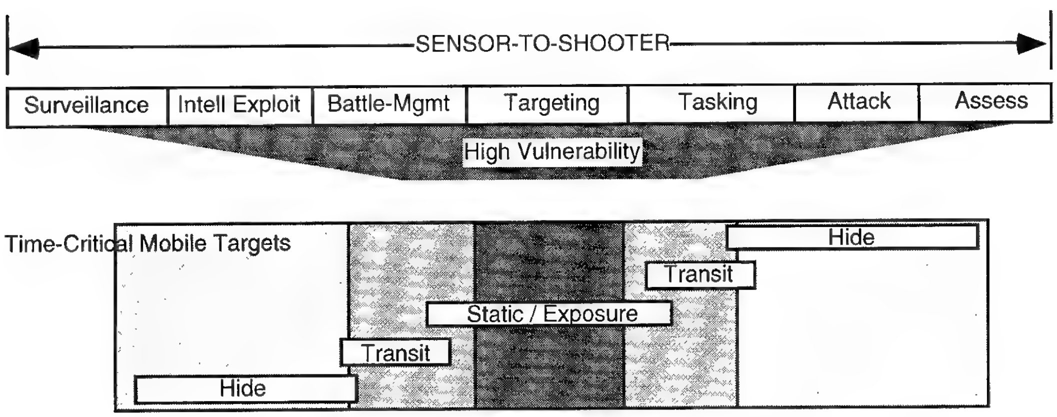

Fig 1. Time-Critical Challenge.

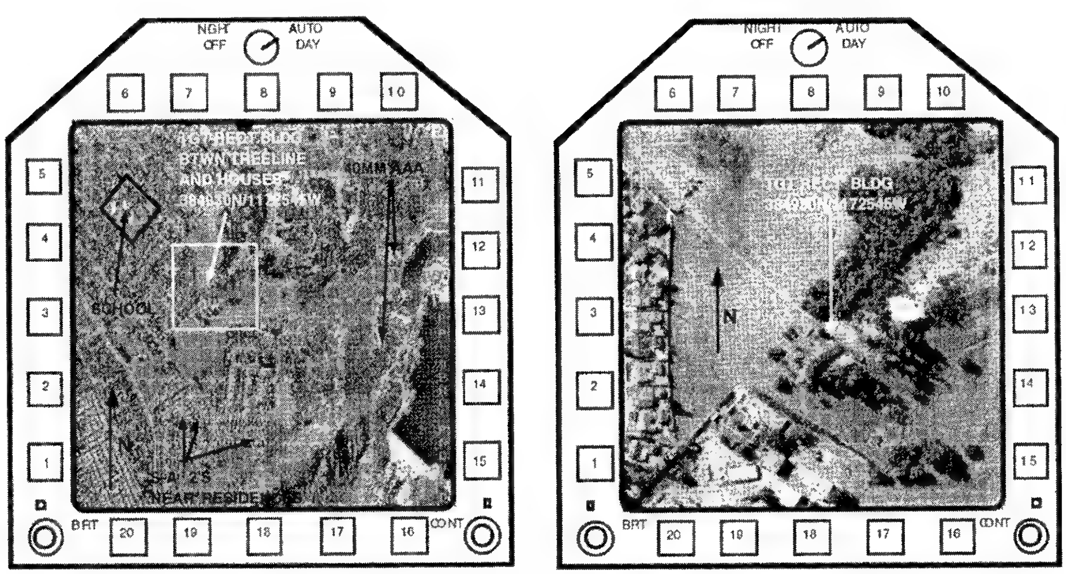

Fig 2. Funnel Navigation.

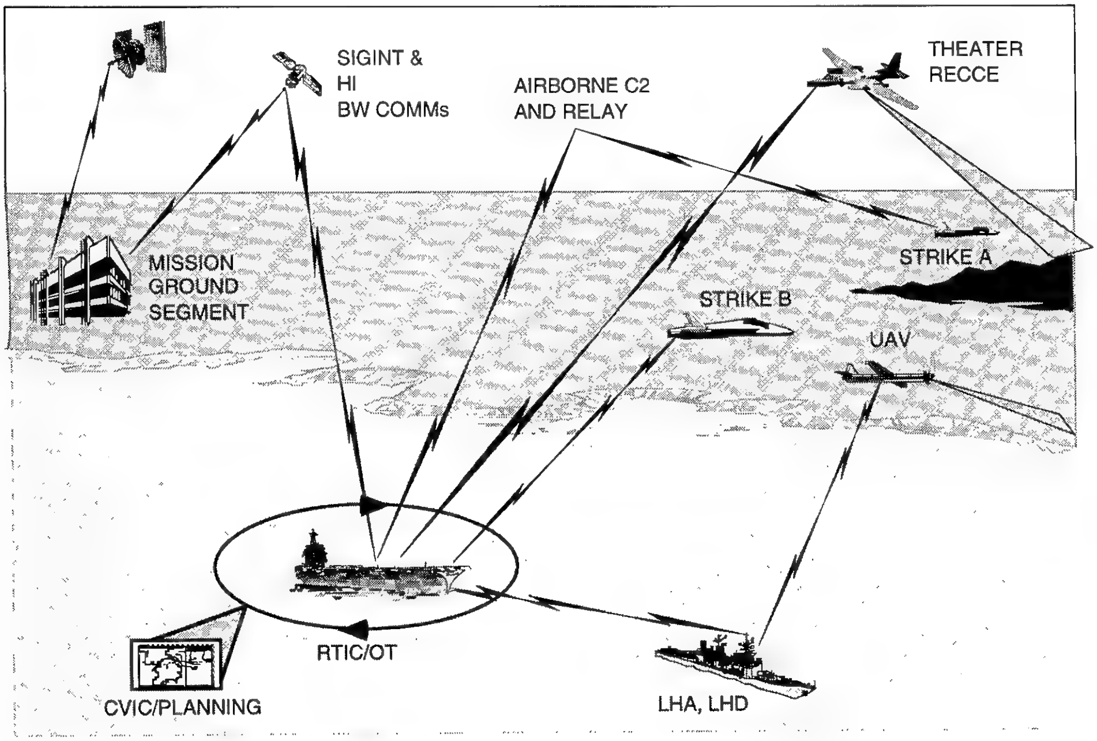

Fig 3. Operational Concept.

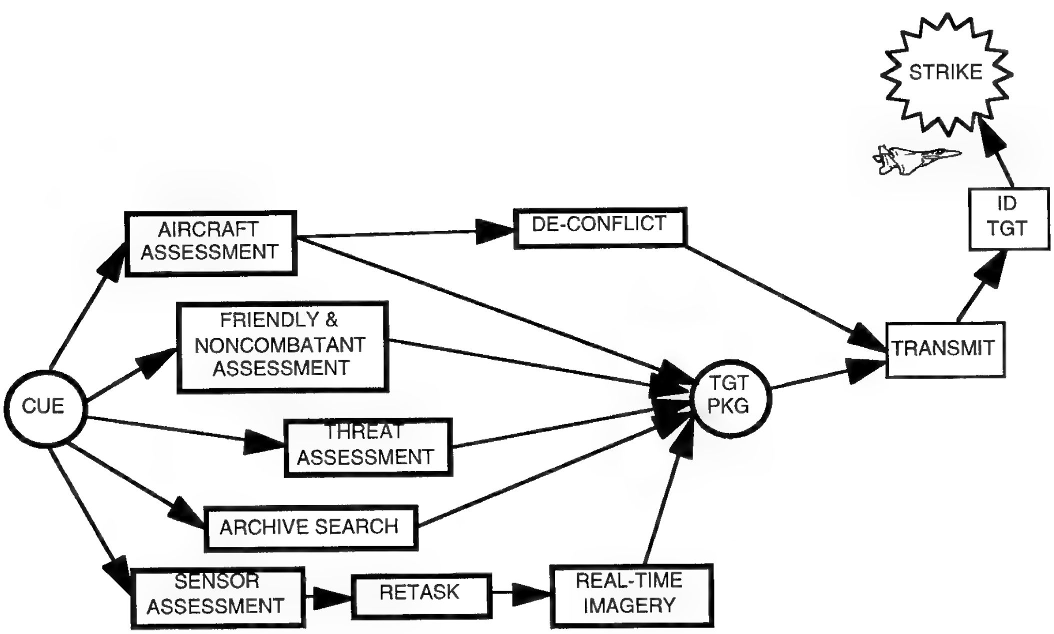

Fig 4. Rapid Targeting Interactions.

to improve accuracy, improve situation awareness, and provide the backbone for rapid targeting and RTIC product generation.

•**Theater Battle Management.** Strike- and unit-level planning TBM systems to generate ATOs and preplan missions, as well as coordinate and avoid conflicts between aircraft retasked in near-real-time as part of RTIC/OT operations. Central to our concept is a RTIC or rapid-targeting cell connected to a Carrier Combat Information Center to address RTIC/OT-specific operations, including the coordination of multisource tasking, intelligence feeds, real-time tasking (RTT), and the production and dissemination of RTIC materials.

•**Command and Control.** Shipboard tracking and communication systems, coupled to the command elements necessary to govern the overall battlespace and ensure that retasked RTIC sorties operate without conflict and with adequate priority within the overall strike plan.

•**Communications.** Composed of intelligence and mission planning local-area and wide-area networks, as well as line-of-site and beyond-line-of-site video and digital data links to weapon systems to support the data transfer of RTIC/OT products.

•**Shooters.** Key weapon systems and onboard processing equipment to receive and process RTIC/OT products, including joint-service strike aircraft (e.g., F/A-18, F-15E), associated precision guided weapons (e.g., JDAM), long-range standoff weapon systems (e.g., JSOW, TLAM), as well as Marine-oriented weapon systems.

TECHNOLOGY BASE

As mentioned, a primary emphasis of our approach is to leverage and compliment past and current RTIC/OT-related projects without duplication of effort and make maximum use of previously developed hardware and software (Fig 5). Related R&D projects conducting core technology development include the following.

•**STS.** A key National Technical Means-sponsored STS core activity to provide overall RTIC technology demonstration support, application of National Technical Means, and prototype multisource intelligence (MINT) exploitation capabilities. These capabilities include rapid data archive retrieval, national-tactical imagery and SIGINT data fusion, targeting materials geopositioning, and tactical data dissemination.

•**Arid Hunter.** A collaborative NAWCWPNS and NSAWC project to enhance the effectiveness of naval strike aircraft against rapidly relocatable targets. A byproduct of Arid Hunter and the Air Force's RTT program was the foundation of the Mobile Intelligence Strike Support Team (MISST) concept that provides a flexible, low-cost, deployable RTIC cell capability. The MISST concept is designed to support distributed personnel and equipment setup at designated facilities (i.e., AOC) or in a stand-alone capacity via collocation and integration in a commercial deployable van.

•**RTT.** An Air Force Wright Laboratory (WL/AART)-led RTT concept development program to evaluate on/offboard concepts for adaptive (offensive) mission management to improve air-to-ground deep-strike operations.

•**OBTEX.** An Air Force Wright Laboratory (WL/AAZT)-led series of offboard targeting experiments (OBTEX) to develop and demonstrate the feasibility to derive target area situation information, SAR-driven precision target coordinates, SAR seeker templates; and program a precision-guided munition in near-real time from offboard resources. This capability includes data transfer to a tactical strike aircraft via line-of-site and satellite communications using Link-16 protocols.

•**ATIMS.** The NAVAIR-led ATIMS program is leveraging modular processing, advanced display, and virtual reality technology to demonstrate a capability that provides enhanced awareness of engagement parameters, alternative mission selection, and more responsive unit-level mission planning and rehearsal. The current program is focused on demonstrating a mission management device on an F/A-18 testbed.

CAPABILITY DEMONSTRATIONS

A key tactical demonstration (Fig 6) and evaluation that has carried the burden of proof for RTIC/OT effectiveness was the Navy-led Arid Hunter series.

•**Arid Hunter Phases I & II.** In the spring of 1994, NAWCWPNS China Lake and the Naval Strike and Air Warfare Center, Fallon, Nev., collaborated on Arid Hunter, a project designed to enhance the effectiveness of naval strike aircraft against rapidly relocatable targets. The staff at Fallon felt that the effectiveness would be increased if the latest intelligence information were available to the strike group throughout the entire mission. The current practice of prebriefing a mission provides the strike group with information that is, at best, hours old by the time the aircraft enter the target area. More than 100 Navy and Air Force aircraft participated in the two Arid Hunter exercises at Fallon from March through May of 1994 (Fig 7).

The purpose of Arid Hunter I was to determine if in-cockpit imagery would be useful in aiding the strike process. Because tactical data links, such as Links-4, -11, and -16, currently can transfer little more than tracking information, China Lake provided an image-processing ground station and transmitter (dubbed the Rapid Imagery Transmission to Aircraft (RITA) system), which was compatible with the Navy's AN/AWW-9 and -13 weapon-wide data-link pods and the Air Force's AN/AXQ-14 system. RF-4 and F-14 Tactical Air Reconnaissance Pod Systems (TARPS) imagery was analyzed in a simulated CVIC and transmitted to aircraft carrying data-link pods. A control group of similar aircraft attempted to find the target using a

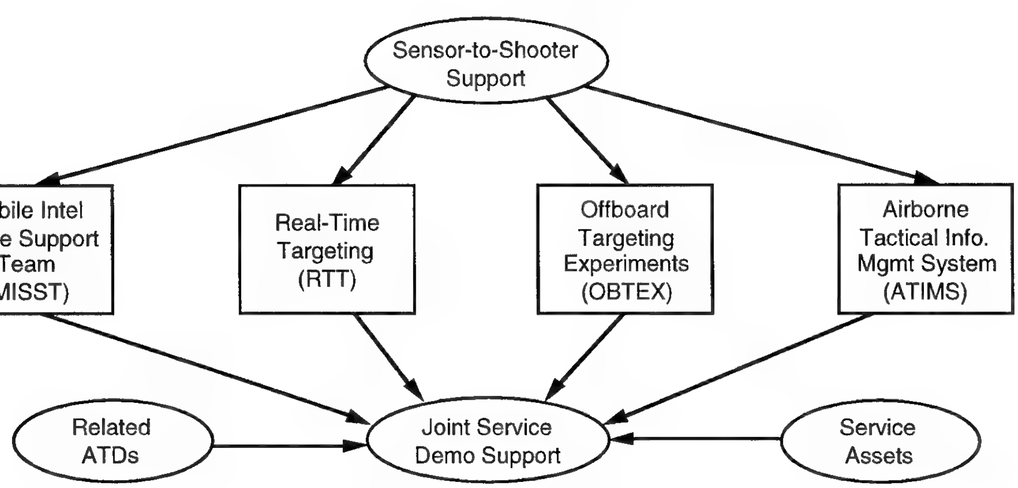

Fig 5. Technology Base.

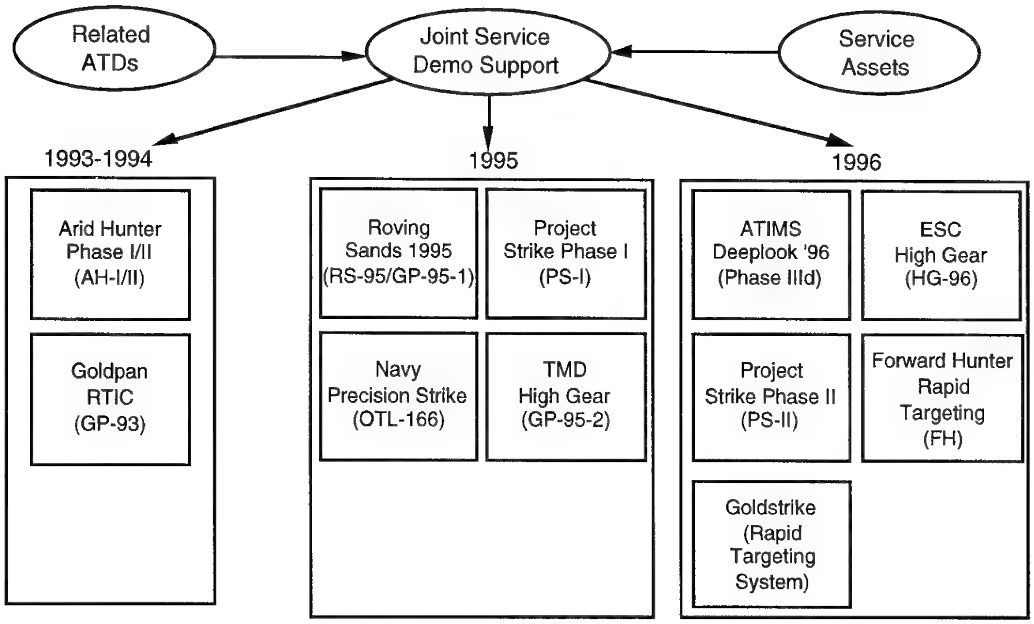

Fig 6. Capability Demonstrations.

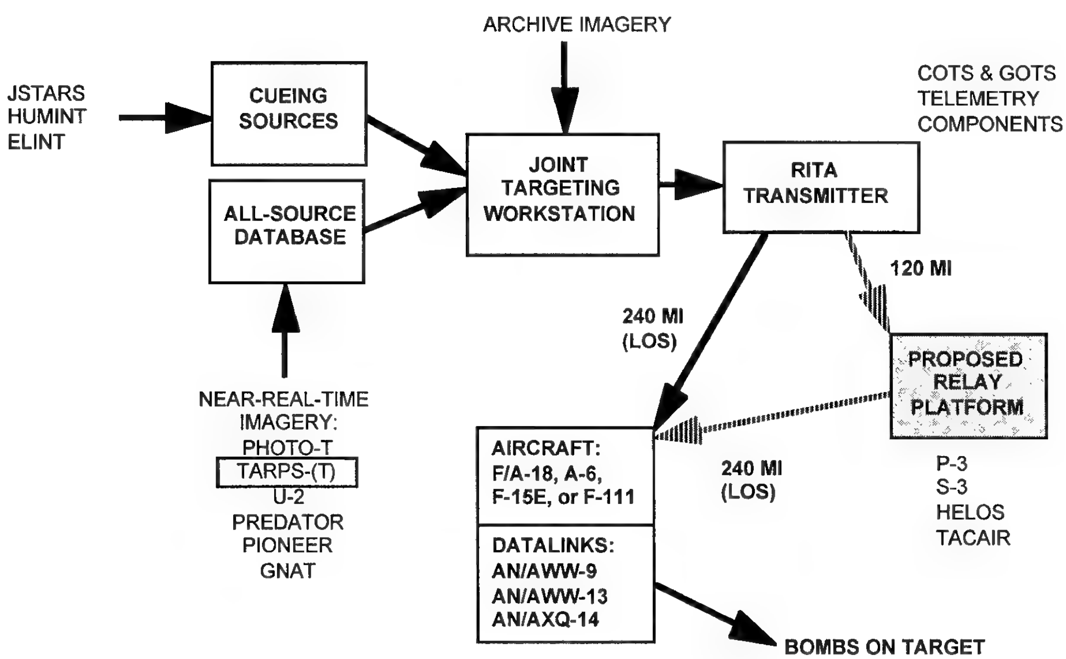

Fig 7. Arid Hunter Data Flow.

standard preflight brief supplemented by accurate GPS coordinates (300 feet).

In Arid Hunter I—against a camouflaged Scud transporter/erector/launcher (TEL) array with nine support vehicles and a decoy—85% of the aircraft without imagery were unable to find the target, and only 15% found anything else in the array (usually the decoy). No one in this group found the actual TEL. With imagery, the results were dramatically better; 73% found the TEL and another 18% found another vehicle in the array. Only 9% failed to find any target (Fig 8). Target-acquisition time, although not measured as part of the test, was significantly less for the group with imagery.

Arid Hunter II took a closer look at the effect of imagery on target-acquisition time. A scenario was used in which the Scud TEL—uncamouflaged and with no support vehicles or decoy—moved daily among 16 locations within an 800-square-mile killbox. Participating aircraft were divided into three groups: (1) killbox coordinates only, (2) GPS coordinates of the target, and (3) GPS coordinates and

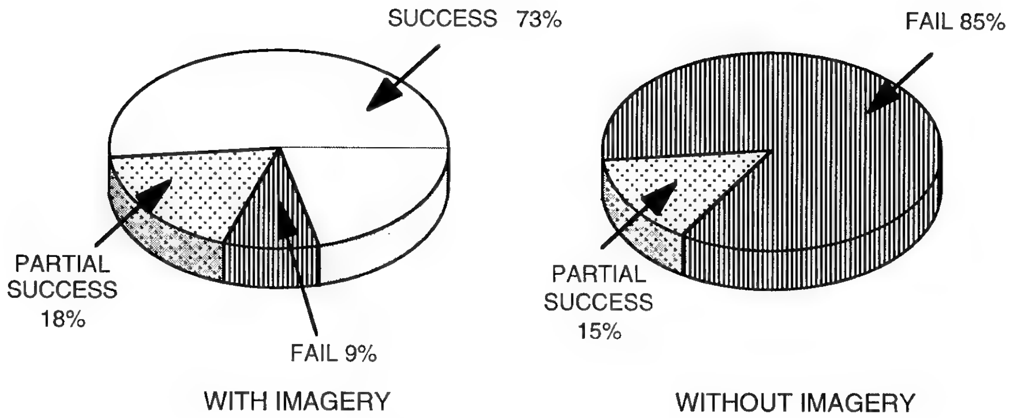

Fig 8. TBM Acquisition Results.

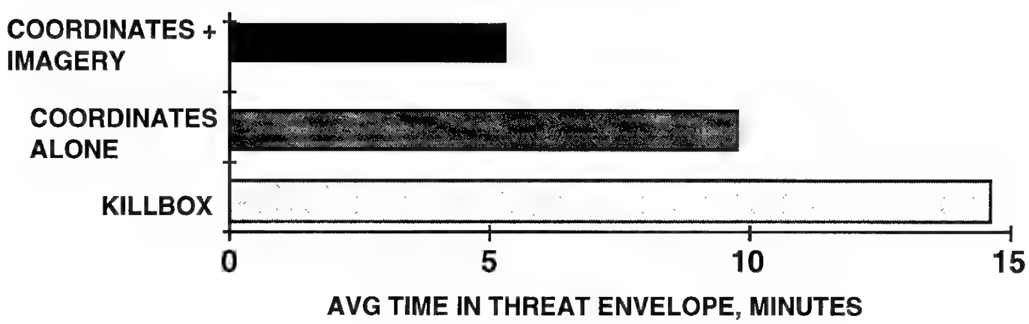

Fig 9. Target-Acquistion Time.

imagery via the data-link pods. In poor weather the average time to find the target was approximately 14 minutes for those aircraft searching the killbox, more than 9 minutes for those with GPS coordinates, and just over 5 minutes for those with GPS coordinates with imagery (Fig 9).

Arid Hunter was similar in design and results to Air Force Project Goldpan '93. From this exercise, the Air Force developed a Mission Need Statement (MNS) for RTIC. The Naval Strike Warfare Center modified this MNS slightly and submitted it for approval. The synergism between the Air Force and Navy RTIC technology communities led the Air Force to choose the NAWCWPNS ground station as the exploitation and transmit elements for Goldpan '95-I at Roving Sands and Goldpan '95-II (High Gear).

Examples of other related proof-of-concept demonstrations that have incorporated the RTIC/OT technologies include the following.

•**Roving Sands '95.** A Joint Chiefs of Staff-sponsored exercise held in May 1995 at White Sands Missile Range, N. Mex. This demonstration included MISST ground station connected to national archive and real-time ASARS and SIGINT collection systems, as well as local Command and Reporting Centers (CRCs) to support generation of RTIC products. F/A-18 and F-15E strike aircraft simulated prosecution of time-critical TBMs (i.e., Scuds). This demonstration also included generation of offboard mission replanning products (e.g., new route and weapon-launch data) sent to the ATIMS flight simulation laboratory using Link-16 protocols over a long-haul DBS link.

•**Deeplook.** A collaborative Utah Air National Guard and NAVAIR ATIMS-sponsored exercise held in June 1995 at Dugway Proving Grounds, Utah. This demonstration included Navy-developed Tactical Aircraft Mission Planning System (TAMPS) ground station equipment tied to an Apache helicopter equipped with tactical data links and real-time situation display. As part of Deeplook '96, this effort is being expanded to include multiple Apache and ground armor vehicles, satellite communications, and MISST-based offboard precision targeting equipment.

•**Project Strike Phase I.** An Air Force ACC/DR and TENCAP (SWC/DOZ)-led demonstration conducted in August 1995 involving B-1B and F-15E strike aircraft in deep-strike precision-attack mission scenarios at the Utah Test and Training Range. Testbed assets were equipped with onboard threat situation displays and image processing equipment to receive offboard imagery-derived RTIC products sent via JTIDS and UHF SATCOM digital data links. The RTIC products were generated by MISST-based targeting and mission planning systems hosted within a simulated AOC at the Hurlburt AFB Battle Staff Training School.

•**OTL #166.** A Navy-sponsored demonstration performed in conjunction with the 1995 Tomahawk Operational Test Launch #166 and JWID '95 to evaluate enhanced collaborative planning and rapid-targeting technologies. During this exercise, the MISST ground station supported pursuit of time-critical fixed targets in simulated engagements at Fallon NAS, including transfer of Pioneeer UAV targeting information to the cockpit to augment national imagery-based targeting.

•TMD-HG (Goldpan '95-II). An Air Force ESC/ZJ-led theater missile defense High Gear demonstration conducted in November 1995 at White Sands Missile Range. High Gear examined the timeline and accuracy requirements necessary to prosecute TBM launchers. This test involved F-15E aircraft equipped with GBU-15 video and JTIDS communications cued from a ruggedized MISST ground station. The ground station was tightly integrated with airborne launch detection and ASARS surveillance sensor platforms to provide RTT cueing and theater imagery, resulting in extremely short time lines from launch detection to target destruction.

•Project Goldstrike. EUCOM requested deployment of the ruggedized MISST ground station and other Goldpan elements to support potential strike operations in the Bosnian theater. The sysem supports F/A-18, F-15E, and A-6 strike aircraft with RTIC products derived from ASARS, UAV, and national imagery. The 5th Allied Tactical Air Force (ATAF) plans include moving the transmitter for better coverage and the addition of RTIC capabilities for the F-16.

RTIC/OT NEAR-TERM GOALS

It is critical at this time to build upon the successes of the past 2 years to establish a near-term operational capability, develop CONOPS, and establish figures of merit in the areas of

•Mission effectiveness	Responsiveness, accuracy, lethality, collateral damage
•Enhanced survivability	Situation awareness, threat avoidance
•Operational flexibility	Retargeting, reallocation, rules of engagement, tactics
•Operational suitability	Operator workload, resources loading, weather restrictions

The lack of these items is a major stumbling block to transition (Fig 10). As a means of addressing these issues, we began the development of an STS infrastructure that, with synergistic programs, will evolve into a production capability at NAWCWPNS to provide custom intelligence products in direct support of operational forces.

The key pieces being put in place in FY96 are several wideband secure communications links to key intelligence agencies; 500-gigabyte imagery servers and exploitation systems at China Lake and Point Mugu sites; and high-bandwidth communications to a customized rapid-targeting cell at the Naval Surface Warfare Center, Fallon. This optimized cell will be made available to the joint services for end-to-end integration and testing of offboard targeting prototypes.

Over the next few years, we plan to provide direct Global Broadcasting System (GBS) uplink capability for connectivity to attack aircraft carriers (CVAs) and amphibious assault ships (LHAs), while we work out the operational and architectural issues using the RTIC cell at Fallon. This aggressive buildup is targeted at our primary objective of facilitating the transition of RTIC/OT technologies, as well as satisfying our near-term goals of developing CONOPS and figures of merit. The cell at Fallon will be used to evaluate the CONOPS against the figures of merit and produce accepted guidance for Fleet units (Fig 11).

The full capabilities of the RTIC/OT concept, as spelled out in the Navy and Air Force MNSs, cannot be achieved by any currently developed system. The final configuration will be a "system of systems," encompassing national and theater intelligence systems, a variety of exploitation systems, and several communication links (Fig 11). For strike aircraft, the most limiting factor has been in the RTIC data link. Current data links used for command and control are not available in sufficient quantities and have insufficient bandwidth to transmit RTIC data in a reasonable amount of time. These wideband digital non-line-of-sight capabilities will not be realized until advanced communications systems are available in large quantities during the 2004 to 2010 time frame. The addition of new or modified data-link transceivers to the F/A-18 or other current tactical aircraft is clearly cost-prohibitive for demonstration or gap-filler purposes.

However, an interim solution is to use transmitters compatible with existing weapon data-link terminals, such as the AN/AWW-9, AN/AWW-13, and AN/AXQ-14.

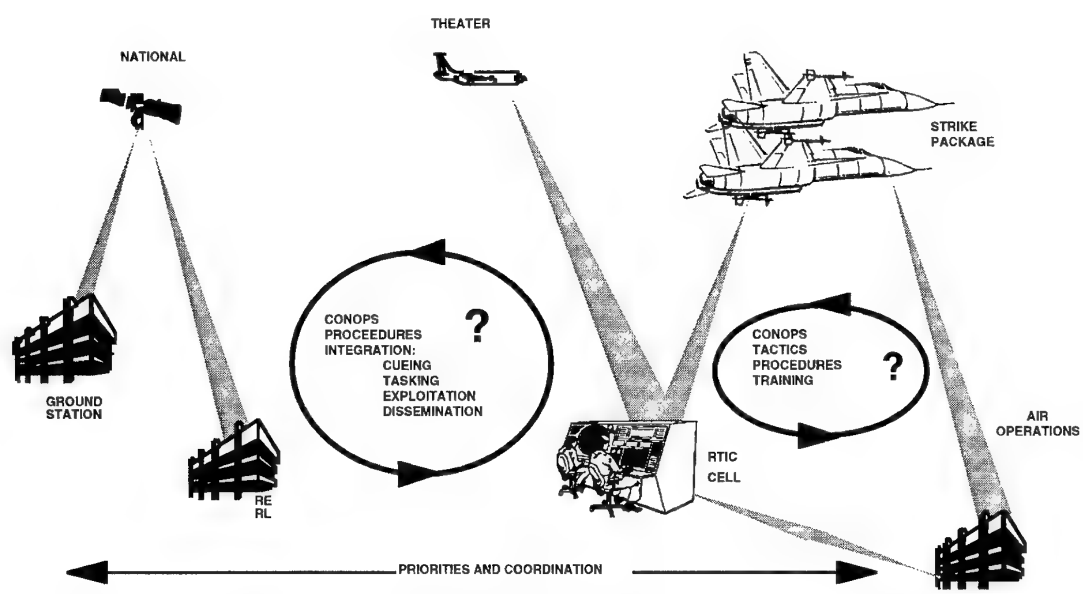

Fig 10. Transition Gap.

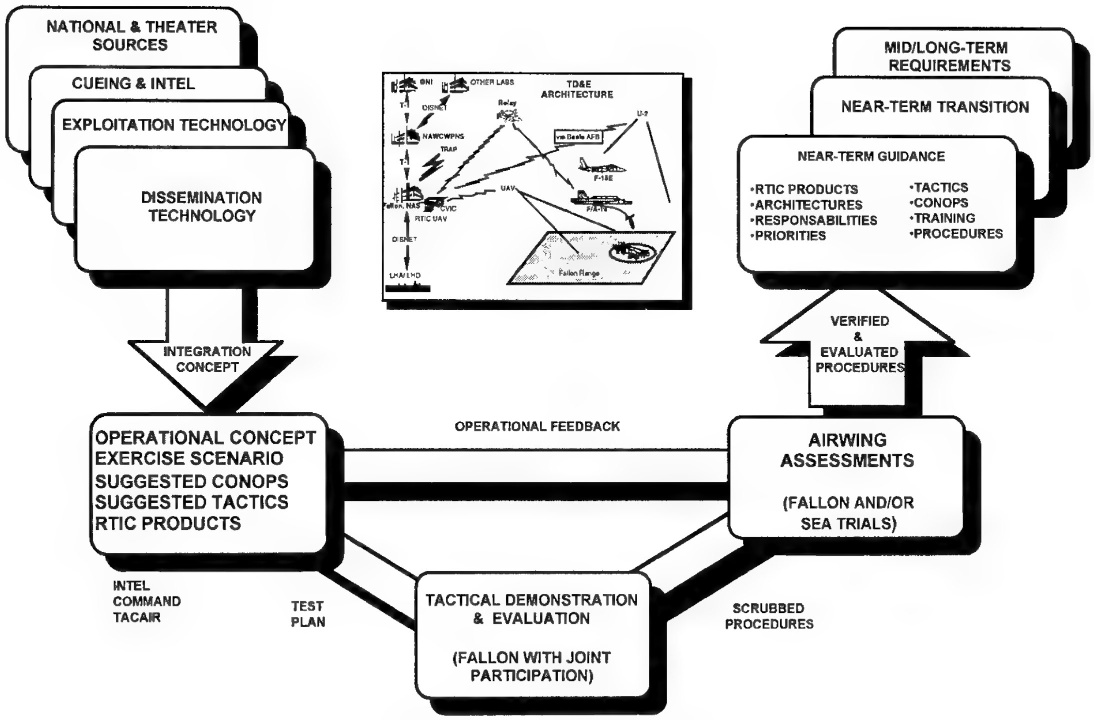

Fig 11. RTIC Cell Operations.

These terminals provide a quick, simple, wide-bandwidth pipeline to the aircraft with Navy/Air Force interoperability, and leverage the 200-million-dollar investment made in these systems over the past 20 years. The Navy and Air Force have about 350 data-link pods for the A-6, F/A-18, and F-15E.

CONCLUSION

Evolving RTIC/OT technology offers great promise in terms of survivability, lethality, and rapid response. Time and again, the Navy and Air Force, along with several other agencies, have demonstrated the value of RTIC/OT and the technical feasibility of several different approaches. The lack of integration and coordination across all the system elements is a serious issue, as is the lack of CONOPS and tactics. Considerable attention needs to be focused in these areas if this technology is to transition in the near future.

Development and deployment of a near-term RTIC/OT system now will provide a considerable experience base for integration with more advanced systems, such as JTIDS/Link-16, when they become widely available. Navy and Air Force users consistently request a relay and storage capability, and these extensions would greatly enhance the value of the current system by easing some of the geometry constraints associated with using the podded receivers and provide a future system development surrogate. Considerable investments have been made to bring RTIC/OT to the strike community. This transition is not complete, but we can see the light at the end of the tunnel.

INTEGRATED PROCESSING

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1. SUMMARY

A review of the modular avionics concepts is presented in light of DOD's mandate to change the military's acquisition process and the recent delivery of advanced modular processing systems developed to meet the demands of the next generation avionics. Future trends in avionics are discussed along with how this will impact the modular standards just now being implemented.

Modular avionics is the most dominant feature of our advanced avionics systems. Initially mandated because of the projected cost advantages, modular avionics also provides significant performance potential. Modular avionics is characterized by configurations that partition the system into building blocks that feature integration, modularity, and commonality. The main focus of these concepts is initially being applied to the digital core avionics for which the F-22 Common Integrated Processor is a powerful and innovative realization. The USAF PAVE PACE and MASA programs extended the current concepts further and the initiatives to integrate commercial-off-the-shelf (COTS) technology has fostered innovative solutions to improve increased availability at reduced costs. Functions within the aircraft will become more integrated requiring innovative approaches to the management of the computer resources and distribution of information.

2. INTRODUCTION

Modular integrated avionics (AVIation ElectrONICS) is the single most significant change in advanced avionics systems. Initially mandated because of the projected cost advantages, modular integrated avionics also provide significant performance potential. With the advent of Pave Pillar, avionics architecture has taken a broader and more important role in avionics acquisition plans. The more recent initiatives, to use already developed components and especially components from the commercial sector, have further broadened this role. Architecture is the framework by which the sub-systems, functions and components and their operation are defined. Previously specified within a program only after mission analysis and functional definition, the Services are undertaking a new acquisition strategy by defining an avionics architecture as a generic solution. Modular architectures refer to architectures such as Pave Pillar which feature modularity through specification of standard modules or building blocks. Avionics includes most electronic equipment installed on an air vehicle including the vehicle management systems and the stores management system.

3. ARCHITECTURE

The architecture may be looked upon as being constructed of several layers of definition. A special and significant layer is that of partitioning. Partitioning is the attribute that gives rise to three key features: integration, modularity, and commonality. These three features are independent of each other and their degree of use may vary greatly across applications. It should be noted that this layer of partitioning applies to software as well as hardware. These three features also impact the efficiency of the architecture in the utilization of the system resources. Integration is defined as the sharing of common tasks or items to gain system fault tolerance and flexibility. Modularity is the partitioning of a system into reconfigurable and maintainable items. Commonality is partitioning to maximize the use of identical configuration items across the range of functions and applications.

Paper presented at the AGARD MSP Symposium on "Advanced Architectures for Aerospace Mission Systems", held in Istanbul, Turkey, 14-17 October 1996, and published in CP-581.

Broad use of modularity and commonality require the application of standards to define significant interface and operating characteristics of various modules or other elements. When these standards become accepted by a broad segment of industry and are maintained in an industry wide forum, they become "open" standards. This enables various companies to provide elements from various applications and to significantly reduce development effort required for a particular application. Thus, non-developmental items (NDI) and COTS items can be applied to sophisticated military applications in ways not previously attainable. Advances in the ruggedness and reliability of commercially available electronics from aviation and automotive markets have been significant, further enabling these applications.

3.1 Integration

As electronic components have achieved higher and higher densities, the integration of more and more complex operations has been an ongoing process. Over the past forty to fifty years, subsystems formerly requiring multiple units were reduced to a single Line Replaceable Unit (LRU) while performing more complex tasks. With new advances, multiple subsystems can be housed in a single unit.

Figure 1 provides a stylized depiction of the avionics architecture transition currently underway.

Most currently fielded architectures, e.g., F-16 and F-15, are "Federated" systems. In these systems, discrete subsystems are interconnected by the 1 Mbps standard avionics multiplex bus (MIL-STD-1553). The transition to an integrated architecture involves grouping like functions together, i.e., signal/data processing, rather than including these functions in separate subsystems.

The following quote is taken from the NAVAIR

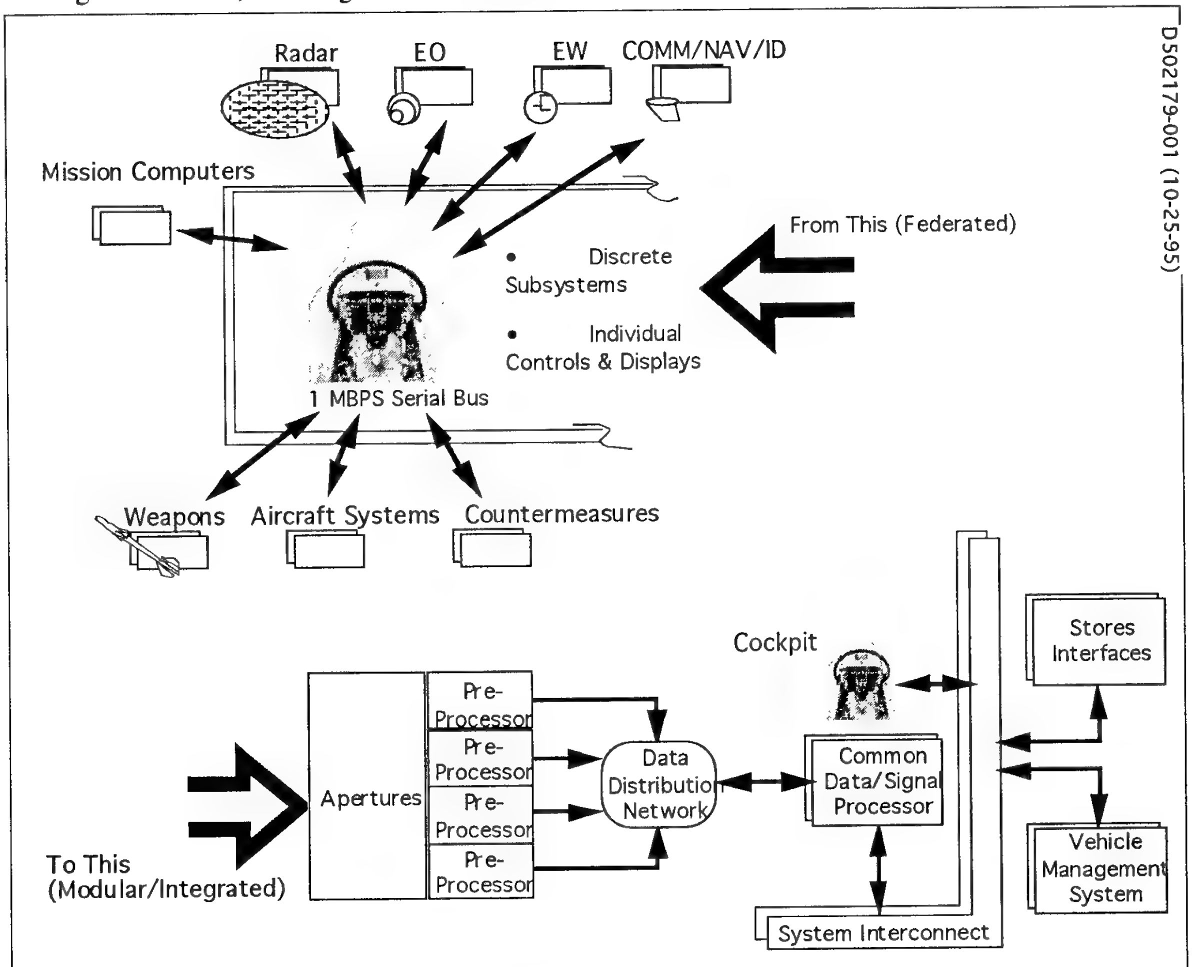

Figure 1. Modern Avionics Architecture. Evolution from current avionics features increasing modularity and resource sharing of common modules through integration.

study entitled "Advanced Avionics Architecture." (1) "Increased processing power and very high levels of circuit integration at the microcircuit level have allowed the capability of some earlier subsystems to be concentrated into a single module. Integrated avionics architectures follow the research approaches pioneered in the Air Force Pave Pillar program and in Navy avionics and modular packaging research of the last twenty years. Architectural standardization under the Tri-Service Joint Integrated Avionics Working Group (JIAWG) promotes the use of integrated avionics architectures packaged in standard modules of a SEM-E form factor and installed in several avionics integrated racks or module cabinets. This approach was originally focused on cost savings through the use of a family of "common" modules that would be applicable to a wide cross section of avionics applications. The Air Force F-22 fighter and the Army RAH-66 Aircraft are developmental aircraft that employ the JIAWG integrated architecture, "common" module approach to avionics."

The approach has been selected as the initial baseline for the Joint Advanced Strike Technology (JAST) program as well (2).

A key driver towards increased integration has been the significant increase in affordability which results from the significant increase in reliability. As the number of individual components has decreased and the reliability of each component has increased, the reliability of the system has increased significantly. Module reliability in excess of 10,000 hours, Mean Time Between Failures, is common. With this level of reliability, two level maintenance is practical, resulting in an additional dimension of savings.

3.2 Modularity

Another independent partitioning feature is modularity. Modularity provides the capability to reconfigure to satisfy a broad range of applications. Several approaches are available ranging from standardizing at the chip level to the subsystem level or line replaceable unit (LRU). The mechanical interface specification, known as Air Transportable Rack (ATR), was developed originally by ARINC, the commercial airlines standards organization, and has achieved wide use in both commercial and military aircraft. The most popular sizes range from 1/2 ATR to full ATR.

More recently, due to the chip densities achievable, complete functions are able to be contained in a single module. This module definition was adopted by JIAWG as previously noted.

3.3 Commonality

The other feature of partitioning is commonality. Commonality, when enabled by modularity, provides the most significant factor in reducing costs for the avionics system by reducing the number of unique module types. A possible disadvantage of commonality is that more modules may be required in the system due to the inefficiencies resulting from applying these common modules to functions – perhaps more efficiently performed by special modules. A trade-off is necessitated between module types and number of modules in a system. Integration without common modules offers few benefits since the sharing of resources across functions requires those resources to be common, and fault tolerance via module sparing becomes impractical.

3.4 Open Systems

The following definition of an "Open System" is from the letter by Dr. Paul Kaminski (3), Under Secretary of Defense for Acquisition and Technology: "Open System Specifications and standards are consensus-based public or non-proprietary specifications and standards for systems and interfaces of hardware, software, tools and architecture."

According to Dr. Kaminski, these open standards are to be used "To the greatest extent practical in the acquisition of weapon systems electronics."

There are several organizations currently regarded as responsible agencies for the development and maintenance of various standards. Some examples are: the Society of Automotive Engineers, Institute of Electrical and Electronic Engineers, Aeronautical Radio, Inc., and VME International Trade Association.

Thus, a working definition of an "Open System" is one in which the specifications are developed by consensus in a public or industry forum and published and maintained by some recognized group. As stated in Dr. Kaminski's definition, a broad range of topics are covered by these specifications. Systems architecture, hardware, and software are specifically included.

3.5 Commercial-Off-The-Shelf

In conjunction with open systems, the government is attempting to reduce the cost of the avionics acquired by procuring commercially available equipment in areas where special built equipment has been acquired in the past. Some of the potential problems to be addressed in the acquisition of COTS equipment are discussed by Trujillo (4). As with open systems, the requirement for the acquisition of COTS-based equipment can be applied over a broad spectrum. COTS can be applied at the subsystem, box, module, or piece part level. And it can be applied to software as well.

Reference 1 defines four criteria that must be met when considering whether to apply COTS for military avionics systems. These are:

- Reliable operation under severe environmental requirements.
- Flight Critical/Survivability designs requiring "Real Time" system response.
- Need for a multi-level Information Security (InfoSec) System which applies throughout the avionics suite.
- Systems must be compatible with military support systems.

4. BACKGROUND

Because of the important role played by real-time processors in sensor systems, their development and application have been led by the avionics manufacturers and are a major product line specialty. As an example of this, a review of this development and application by Hughes Aircraft Company will provide insight into processor developments for real-time applications. Since 1949, Hughes has successfully developed, produced, and supported sensor systems of wide variety and progressively advanced capability of avionics, ground-based, shipboard, and space usage. Hughes has pioneered many advanced processor technologies including the first airborne digital computer, real-time digital synthetic array radar processor, operational airborne fast Fourier transform (FFT) signal processor, programmable airborne FFT signal processor, and the common integrated processor.

Recently, processor systems have been produced for the F-14, F-15, F/A-18, TR-1, B-2, C-17 avionics and other major systems. This broad experience in processor technology and an in-depth understanding of the applications and system architecture were key elements in being selected by the Lockheed F-22 Advanced Tactical Fighter team to develop the Common Integrated Processor (CIP) for the sensor and mission processing. Following a successful Demonstration/Validation phase and an Engineering/Manufacturing Development Phase, the first production processor for the F-22 was delivered in August of 1995.

5. PROCESSOR DESCRIPTION

Within the avionics architecture, the Hughes Modular Processor (HMP) line supports all signal processing, data processing, digital input/output (I/O), and data storage functions using a single, integrated hardware and software design. Using fully integrated signal and data processing, the HMP, as in the F-22 CIP, is distinguished from federated or partially integrated architectures because it provides the requisite high performance computing power with lower installed weight, volume, power, and cost. This integrated architecture incorporates the PAVE PILLAR concepts and implements Joint Integrated Avionics Working Group (JIAWG) standards. These include the PI-bus and TM-bus and the Dual Data Processing Element (DDPE) which employs a high performance 32-bit Central Processing Unit (CPU), the Intel i960™ Reduced Instruction Set Computer (RISC) processor. The i960 extended instruction set architecture (ISA) is one of two 32-bit instruction set architectures recognized by the JIAWG as the basis for standardization of 32-bit embedded avionics computers. The PI bus standard is now "open" in the commercial sector and is defined by SAE Standard 4710.

5.1 Overview

An overview of the Hughes Modular Processor product line is shown in Figure 2. It ranges from a large, integrated avionics processor, seen in Figure 2a, to smaller integrated signal/data processing machines and even less complex data processors, seen in Figure 2d. In large-scale avionics processing applications, the total available signal and data processing performance is massive: over 350 MIPS general purpose processing and 9 BOPS of parallel programmable signal processing throughput. This performance is indicative of the

performance for the HMP Common Integrated Processor configuration.

5.2 Architecture Family

The avionics processing configuration provides sensor processing functions for Integrated Communications Navigation Identification (ICNIA), Integrated Electronic Warfare (INEWS), fire control radar and supports infrared search and track. All mission avionics functions, including display processing, are also included. This diversity of application is supported by an extensive set of low-latency real-time operating system services and easy to use software tools – all developed in Ada. The support software tools are hosted on Digital Equipment Corporation VAX computers.

The HMP architecture is 'open.' Along with a Hughes-supplied Signal Processing Element (SPE), three other specialized signal processing elements developed by other suppliers have been successfully integrated, as well as fiber optic transmitter/receiver, avionics bus interface (ABI) input/output, and Standard Electronic Module-E (SEM-E) modular voltage regulator modules. The open architecture was achieved by developing detailed hardware and software interface documentation of the HMP architecture, hosting working group meetings with module suppliers, and holding detailed design reviews of the processor and vendor-supplied modules. VHDL modeling and standard interface components will further enhance the ease of open architecture realization.

To date, over 600,000 lines of Ada application code has been developed and integrated on these HMP machines by seven other companies and by Hughes. This high intensity, multi-user, multi-application user base has resulted in rapid maturation of the support software tool set. In addition to application software, the Hughes developed plus vendor-supplied support software exceeds 800,000 lines of code.

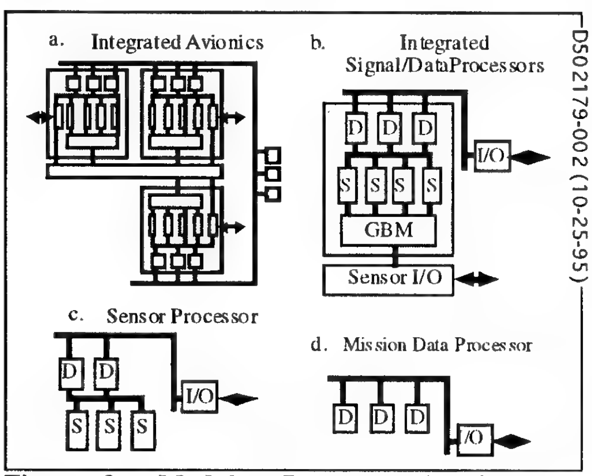

Figure 2. Modular Processor Architecture Enables Expansion to Fit the Application.

High Performance SEM-E form factor processing modules were developed and demonstrated as part of the ATF program Demonstration/Validation phase in 1990. The Dual Data Processing Element (DDPE), using the Intel i960 RISC CPU, implements the special memory access control provisions of the CPU's extended architecture, supporting a trusted computing environment. The DDPE provides 30 MIPS throughput and 4 Mbytes of SRAM memory implemented.

The SPE, demonstrated in 1995 in SEM-E form factor, is programmable pipeline architecture array processor with 450 MOPS fixed point and 125 MOPS floating point performance. The SPE is macro programmable and features an extensive instruction set, directed at radar and electro-optical signal processing performance. It provides a 12:1 improvement in throughput per unit of area, weight, and power compared with the previous generation F-15E SPEs. Arrays of SPE may be used for high throughput applications and the cluster architecture supports the low overhead control of multiple, parallel processors operating on shared data.

5.3 Modular Approach

The integrated signal and data processing of the HMP, coupled with the efficient cluster architecture, minimizes the required interface modules and processing/memory elements, as well as physical interfaces. In addition, high density packaging technologies were developed permitting entire functions to be fabricated on a single SEM-E module. For instance, the DDPE SEM-E module includes the Intel i960MX RISC processor, two dual telemetry (TM) bus interfaces, a PI-bus interface, start-up ROM, fault log, and 4 Mbytes of high bandwidth SRAM memory. Figure 3 shows the DDPE module.

As developed for the F-22, the HMP products use a liquid cooling concept. The cooling liquid flows through a serpentine path in the center of the two sided module. This technique achieves high cooling efficiency enabling high power dissipation. For retrofit applications where liquid cooling is not available, different form

factors have been successfully used. For example, an upgrade to the AN/APG-73 radar used in the Navy F/A-18, uses a Standard Avionics Module (SAM) design approach utilizing air flow through in the module core. Conduction cooled examples have been developed, as well.

5.4 Support Software

One of the most significant advantages of modular common integrated processing is the support software user base is maximized and focused on the use of a single set of tools. As a processor developer, Hughes has used the HMP tools to develop, debug, and test hundreds of thousands of lines of signal and data processing software. However, on the ATF Dem/Val program alone, the Lockheed, Boeing, General Dynamics team developed over 500,000 lines of Ada and 150,000 lines of signal processor code. This has accelerated the maturity of the HMP tool set – and has resulted in significant optimizations for a broad spectrum of users.

The HMP software development products comprise a complete Software Engineering Environment. Three of them are of special note: the Ada Compiler, User Console Interface and Debug, and the Ada Operating System.

Hughes has funded Irvine Compiler Corporation (ICC) to develop the Ada compiler. ICC was put under contract in 1987, participated in the ATF Dem/Val program, and is the compiler source for the ALR-67 Advanced Special Receiver program. ICC developed their Run Time Systems to a common interface design optimized for the Hughes Core Operating System (OS). ICC markets their i960 32-bit compilers directly or they can be purchased through Hughes as a package with other HMP support software products.

The HMP user console software provides debug access to HMP computing elements, a real time symbolic debugger, and the low level instruction tracing access unique to the i960MX. Multi-user capability enables multiple concurrent debug sessions to be run with independent Ada applications executing on the host HMP.

The Hughes Core OS is the first 32-bit real time multi-program, multi-tasking operating system written in Ada. Now in its fourth generation of development, the Core OS uses a preemptive, priority-driven Ada tasking model with task priority arbitration across program boundaries. It provides Ada program support, semaphores, I/O support, and hardware/software debug support. In addition, it supports the HMP software architecture which is based on directed graphs that allow computational tasks to be decomposed into tightly coupled jobs executing concurrently on multiple processing resources.

5.6 Systolic Cellular Array Processor

The Systolic Cellular Array Processor (SCAP) is the latest of the modular processor components in the Hughes product line. It is built using a Single Instruction Multiple Data Stream (SIMD) architecture. A single module of the current design is capable of performing 3.2 billion floating point operations per second. The SCAP has been designed to operate with the same global bulk memory interfaces as other Hughes modular products. Figure 4 shows air flow through the Standard Avionics Module physical configuration that exists today. Hughes plans to develop a Standard Electronics Module (SEM) configuration using its advanced large panel High Density Multichip Interconnect (HDMI) technology.

5.7 Hughes Modular Products (COTS)

While there many applications where the highest component density possible is required, as in the F-22, there are other applications where advantages can be gained by using less dense packaging concepts. Hughes has applied the well known Versa Module European (VME) to the i960 32-bit CISC processor to achieve a low cost processor module.

5.7.1 Versa Module European

While there are many available back plane bus specifications available, the one that is receiving the most attention in the commercial avionics marketplace is the VME. The VME bus development was led by Motorola in the late 1970's. There are currently two Institute of Electrical and Electronic Engineer (IEEE) standards which define the bus and card interface. IEEE Standard 1014.1 is the VME bus specification. IEEE Standard 1101.2 defines the physical characteristics of the Conduction Cooled Eurocard. The forum for the development of advances to these standards is the VME International Trade Association (VITA). The specification to expand the interface to VME 64 is currently being circulated for approval by industry. Processing system components, using the VME format, are

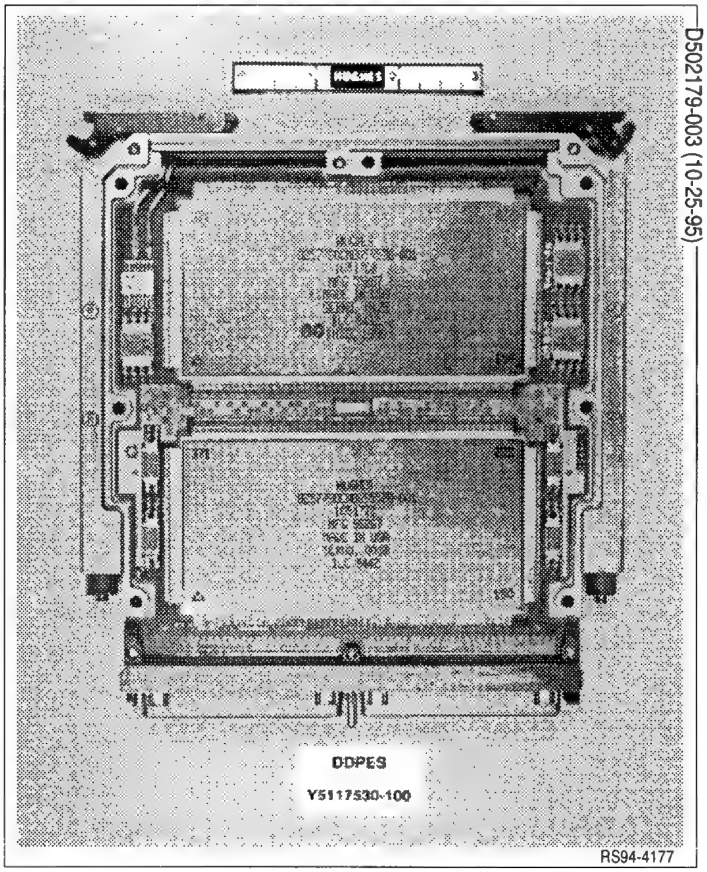

Figure 3. Data Processing Module Line Replaceable Module Layout. High Density Packaging Featuring SEM-E Format.

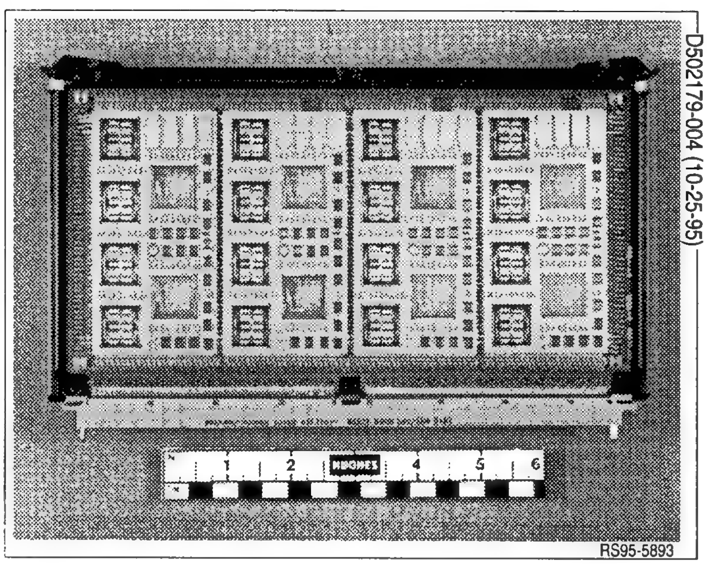

Figure 4. The Physical Configuration of the Present SCAP Air Flow Through Standard Avionics Module. An advanced high throughput module extends performance.

available from many manufacturers. Thus, the VME standards provide an excellent framework for building COTS based systems.

Hughes has designed an advanced processing module using the 64 VME module definition and the VME 64 back plane bus. The card is shown in Figure 5. The card uses the same Multi-Chip Module (MCM) and i960 processor used in the HMP applications described above. By using a frequency of 20 MHz, the power dissipation is kept to less than 30 watts, enabling conduction cooling to be used. The temperatures are low even at 30 watts, therefore reliability is high. The Software Engineering Environment is the same used for the F-18 and is mature and widely available. The card is intended for retrofit applications and will be available in late 1995.

The on module interface uses the PCI bus definition. This means as future developments in CPU's occur, they may be substituted on the board with minimum redesign.

6. LEGACY SYSTEMS

While the future direction of avionics systems is undoubtedly toward higher and higher levels of integration, the dilemma imposed by the rapid advances of electronics is that the life of the current aircraft systems is thirty to fifty years, even longer in the case of some bombers and tankers, while a new generation of data processors appears about every eighteen months. Five years is the maximum length of time that a commercial manufacturer expects to continue manufacturing a given product.

Parts obsolescence, while always a problem, becomes more of a concern in this environment. Advanced technology solutions to parts obsolescence include use of plastic encapsulated microelectronics (PEMS) used extensively in commercial applications and alternately mounting bare die on circuit boards that use printed wiring that can accommodate differences in die size and interconnects. Processes must include practices such as the use of VHDL that capture design detail and enable ease of transition to the next generation technology. Another major issue as technology upgrades are pursued, is the impact on the existing software. This software usually represents a large investment and minimizing the changes to it is usually desired.

Incremental upgrades may be the affordable approach taken that captures existing software and necessary infrastructure but moves to a more open architecture and enables new functions to be added using advanced technology. It is against this background that

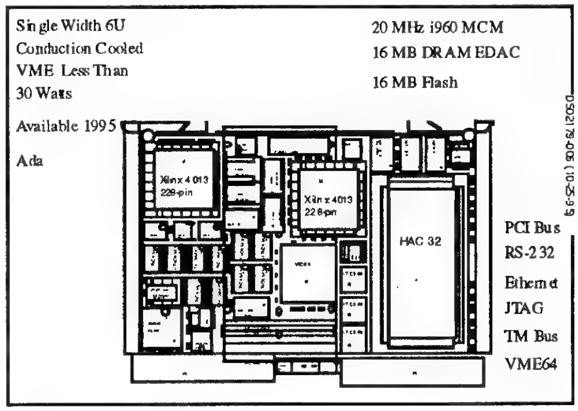

Figure 5. Intel i960 Processing on VME with a Mature S/W Engineering Environment (SEE)

Hughes has developed a single chip upgrade for its Mil Std 1750 processor. This processor, originally developed by Delco Electronics, is employed in processing applications in the F-16 fire control computer, the Lantirn pod computer, the MADAR computer for the C-5, and the mission computer for the C-17. The single chip version replaces the original twelve chip computer and achieves a through put of 4 MIPS with 30 MHz clock speed. Prototype cards in the LANTIRN Configuration were delivered to Warner Robins AFB, GA for evaluation in August 1994. The software developed for use in the previous multichip version was loaded and successfully run. The LANTIRN configuration is a modified 4" x 6" card (1/2 ATR). A 1/2 ATR version will be demonstrated in an F-16 fire control computer next year. This single board computer is illustrated in Figure 6.

7. CONCLUSION

A review of the Hughes processor product line indicates a broad range of products from very high performance and innovative designs to those systems with high utilization of COTS. These products can be applied over the spectrum of required performance levels through module expansion and yet retain the same supporting architecture and infrastructure.

The products applied to the F-22 exemplify the high performance products where issues of data security and packaging for extreme environments have been addressed. Adaptation to commercial practices requires that designs use

open architectures and robust designs to mitigate the obsolescence problems due to faster technology advances. The use of OS and COTS components from modules to components to software development environments needs to be increased to provide the lowest cost solution over the life of the system that is compatible with the overall performance requirements of any specific weapons system.

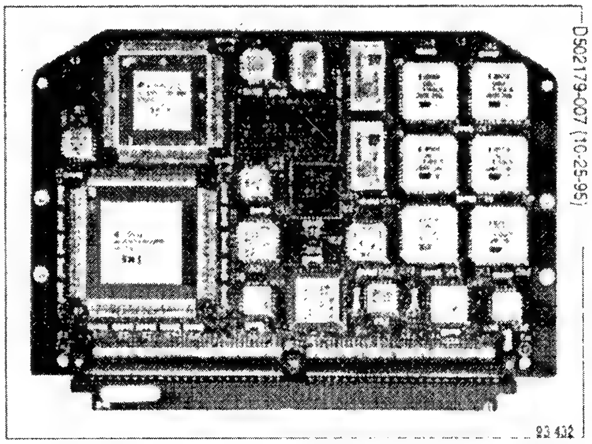

Figure 6. Magic V Single Chip MIL-STD-1750 Single Board Computer enabled the incorporation of advanced technology yet capturing the previous investment in software.

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A Modular Scaleable Signal Processor Architecture for Radar and EW Applications

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SUMMARY

Daimler-Benz Aerospace, Ulm has developed the Advanced Programmable Signal Processor (APSP), a modular, scaleable and programmable multi-Gigaflop machine based on studies sponsored by GMOD. The modular architecture allows an easy tailoring to quite different requirements in signal processing and pattern recognition for Radar, Sonar, Electro-optical sensor applications, e.g. from small non-coherent radar and EW systems up to sophisticated airborne multimode pulse doppler radars or complex ground or ship based multichannels radars.

From an architectural point of view, the APSP comprises clusters of single chip floating point processors (Texas Instruments TMS320C3x [1] digital signal processor which can perform 32-bit floating point calculations at a 60 Megaflop rate), special partially programmable modules (based upon off-the-shelf VLSI-chips), multipurpose memory modules and multipurpose interface modules. The APSP comes with comprehensive Software and Tools including the real time multiprocessor operating system APOS. The modularity and scalability in Hardware and Software offers the possibility to tailor the signal processor performance to the application, while preserving options for growth potential. Furthermore modifications in the processing algorithms are done via software changes, without costly hardware redesign.

This article focuses the major aspects of the APSP in Hardware, Operating System and Software Tools and shows the implementation of a small and a high performance application.

List of Symbols

APOS	APSP Operating System
APSP	Advanced Programmable Signal Processor
CFAR	Constant False Alarm Rate
DSP	Digital Signal Processor
DTN	Data Transfer Network
FFT	Fast Fourier Transform
GFLOPS	Giga (10^9) Floating-Point-Operations per second
GMOD	German Ministry of Defence
GPIO	General Purpose Input/ Output
HW	Hardware
IPU	ISAR Processing Unit
ISAR	Inverted Synthetic Aperture Radar
LC	Local Controller
MC	Master Controller
MFLOPS	Mega (10^6) Floating-Point-Operations per second
MM	Mass Memory
OS	Operating System
RAM	Random Access Memory
SAR	Synthetic Aperture Radar
SP	Signal Processor
SW	Software
VLSI	Very Large Scale Integration

1. INTRODUCTION

GMOD sponsored studies were the basis for the development of the APSP, a modular, scaleable and programmable signal processing system developed for a wide variety of signal processing applications e.g. Radar, EW, EO sensors, Sonar,.. in ground-based and airborne systems.

The APSP is designed as a complete signal processing system with five layers as Fig. 1-1 shows. The top layer is represented by the application which is mapped by means of the layers below to the bottom layer, which is the APSP hardware.

Paper presented at the AGARD MSP Symposium on "Advanced Architectures for Aerospace Mission Systems", held in Istanbul, Turkey, 14-17 October 1996, and published in CP-581.

The APSP is designed as a hierarchically coupled multi processor system, that can be simply adapted to performance requirements between 300 MFLOPS and several GFLOPS. The APSP provides fail-soft capability by parallel processing, single instruction multiple data (SIMD) and multiple instruction multiple data (MIMD) performance and has a long-term architecture with high growth capability. The APSP is programmable in 'C', provides a user-friendly operating system that supports application programming without special knowledge of hardware and comes with system configuration tools to simplify the distribution of application to the hardware.

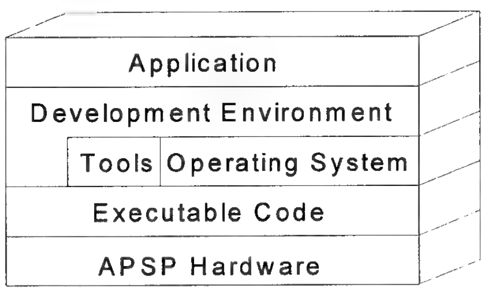

Fig. 1-1 APSP System Architecture

2. APSP Hardware

The APSP can be seen like a box of building blocks that are taken to adapt the APSP hardware to application requirements. The smallest building block is a module. All modules are realised as Double Eurocards (233 x 160 mm). All modules are available in a commercial version (0°C to +70°C) and a ruggedized version (-40°C - +85°C).

The APSP is built up with two kind of modules, see Fig. 2-1,

- APSP modules
- VMEbus modules

The APSP modules perform the signal processing functions These modules communicate via the Data Transfer Network (DTN) using a message passing protocol. Two versions of the DTN are available:

1. A 32 Bit Bus with 40 Mbytes/sec data rate for lower performance systems.
2. A Star topology with 8 nodes, allowing 4 simultaneous point-to-point connections for high performance systems. The maximum data rate is 280 Mbytes/sec.

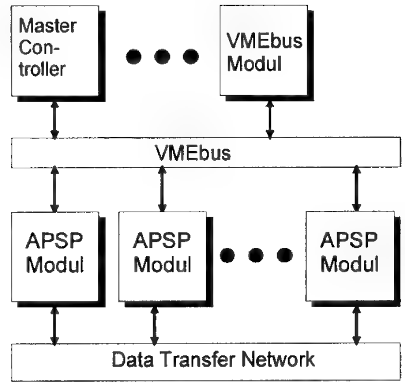

Fig. 2-1 APSP Block Diagram

The APSP modules are subdivided in two groups, fully programmable and special partly programmable modules (SPPM). Fully programmable modules are based on clusters of programmable signal processors TMS320C3x from Texas Instruments [1] and provide the greatest flexibility. SPPMs contain dedicated processing hardware, e.g. FFT processor, to achieve a very high performance by executing a limited number of processing functions with limited flexibility.

The VMEbus has a twofold role in the APSP:

1. It serves as the Local Control Bus of the APSP. By means of an off-the-shelf VMEbus CPU, called Master Controller (MC), the APSP modules are controlled and monitored.
2. It supports the extension of the APSP by off-the-shelf VMEbus modules, e.g. SCSI Interface, Graphics controller etc.

The following APSP modules are available:

- Processing Element, the basic module of the APSP.
- General Purpose Input/Output (GPIO), is used to build clusters of PEs.
- Doppler Processor (DOP), is a special partly programmable module for dedicated high performance signal processing functions
- Mass Memory (MM), provides additional memory area of 16 Mbytes RAM.

- DTN Star Controller, connects up to 8 DTN nodes and performs point-to-point (4 pairs), multicast and broadcast communication.
- APSP Serial Input/Output (APSP-SIO), provides the input/output interface to a frontend.
- Master Controller (MC), supervises the APSP modules. It is a general purpose VMEbus Single Board Computer based on the Motorola 68040 processor.

2.1 Processing Element (PE)

The Processing Element is the basic module in the APSP system. It contains five TMS320C3x [1] Digital Signal Processor (DSP), see Fig. 2-2. Each can perform 32-bit floating point calculations at a 60 MFLOP rate, that gives an overall performance of 300 MFLOPS.

One DSP is used as Local Controller (LC) for flexible control of the PE e.g. housekeeping, I/O data transfer, MC communication, etc. The four other DSPs act as servers that are subdivided into two couples connected via a shared 32-bit bus to a memory bank of 1 MBytes.

All internal busses of the PE are connected to the 4-port crossbar switch, that allows two simultaneous point-to-point connections. The PE has two interfaces: The DTN Node handles communication with the DTN. Via the VMEbus the MC has access to the onboard RAMs.

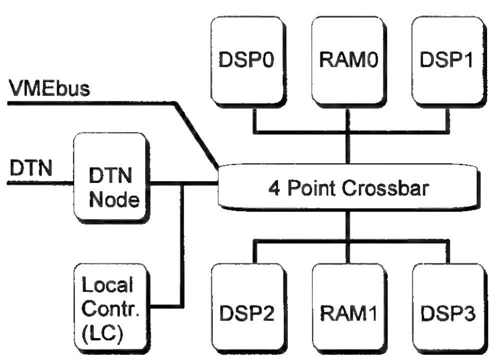

Fig. 2-2 Processing Element Block Diagram

2.2 General Purpose Input / Output (GPIO)

The GPIO is used to connect up to four PE modules without interfering the DTN. Furthermore it connects the PE with the VMEbus and provide additional RAM for the PE. It contains 1 DSP processor TMS320C31 as LC for flexible control of the GPIO e.g. housekeeping, I/O data transfer, BIT etc., see Fig. 2-2.

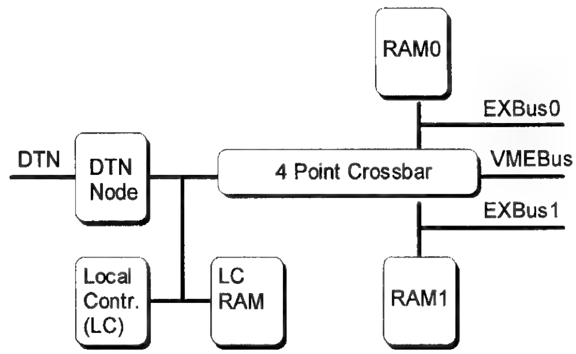

FIG. 2-2 GPIO Block Diagram

The GPIO has four interfaces: The DTN Node handles communication with the DTN. The EXbus0 and EXbus1 interfaces connect the PEs to form a Programmable Processing Module (PPM), se Fig. 2-3 The VMEbus interface gives the Master Controller access to at all RAMs in the GPIO and the connected PEs.

All internal busses of the PE are connected to the 4-port crossbar switch, which allows two simultaneous point-to-point connections (e.g. DTN with RAM0 and VMEbus with RAM1).

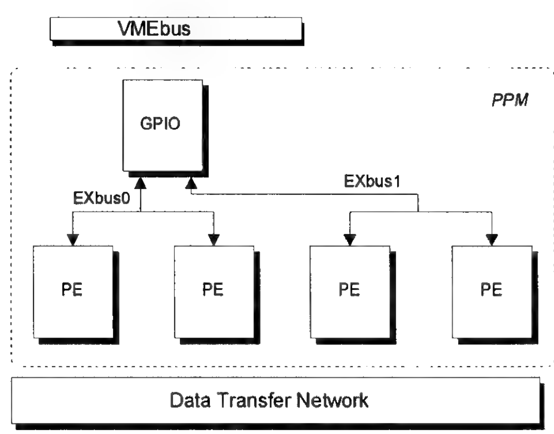

FIG. 2-3 Programmable Processing Module

2.3 Doppler Processor (DP)

The Doppler Processor, see Fig. 2-4, is a special partly programmable module dedicated to high performance signal processing functions like FFT, Fast Convolution, Complex multiply, Magnitude

square calculation. The FFT processor is a Sharp LH9412Y-33 [2] providing 400 MFLOPS of 24-bit block floating performance. The FFT processor is connected to three 48-bit memory banks, RAMA with a capacity of 256 Kwords, RAMB and C with 128 Kwords each, to give an optimal support for the multi-pass architecture of the LH9412Y-33. So a performance is achieved for complex FFT of 100 μs for 1K points and 374 μs for 4K points.

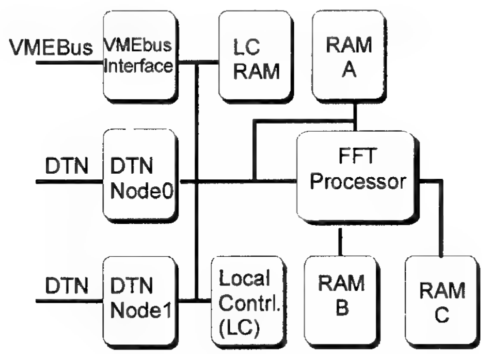

Fig. 2-4 Doppler Processor Block Diagram

The DP contains also one DSP TMS320C31 [1] as Local Controller (LC) for flexible control, e.g. FFT kernel control, DTN protocol handling and post-processing functions. The LC RAM has a capacity of 512 Kbytes. The DP has two DTN interface to support flow-through processing with a max. throughput of 5.5 Megasamples/sec of 16 bit complex data.

2.4 Mass Memory (MM)

The Mass Memory provides additional memory area of 16 Mbytes RAM, see Fig. 2-5. It is accessible via two independent DTN Interfaces and the VMEbus. The MM is also equipped with a TMS320C31 processors as Local Controller that performs flexible addressing, e.g. corner turning, and signal processing tasks on the memory content e.g. CFAR computation without interfering a PE.

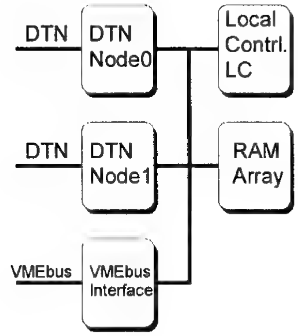

Fig. 2-5 Mass Memory Block Diagram

2.5 Data Transfer Network (DTN)

The Data Transfer Network is a high performance network to exchange data between APSP modules. It is designed for communication in asynchronous parallel multiprocessing systems. The basic DTN cluster is implemented by a star topology in which all nodes are linked via a central switch(Crossbar) which transfers the data according to the central control system, the DTN Star controller, see Fig. 2-6.

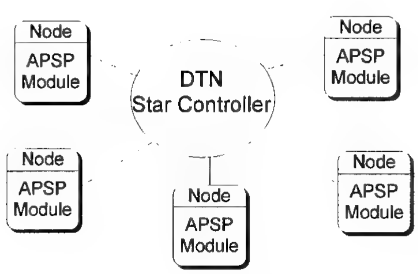

FIG. 2-6 DTN Configuration

The **DTN Star Controller** handles the data and control transmission within the DTN see Fig. 2-7. The Star Controller analyses requests for communication from the nodes, manages the data path switching and reports transfer errors. The Star Crossbar Switch connects the data paths in the network according to the settings from the Star Controller.

The Star Monitor traces the DTN activities and permits the Master Controller to monitor and control the DTN behaviour via a serial link.

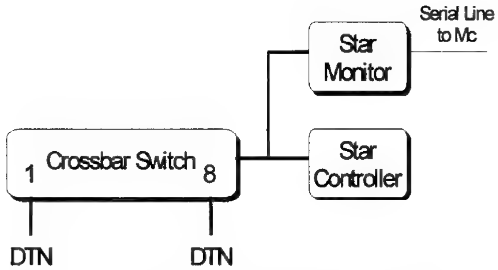

FIG. 2-7 DTN Star Controller Block Diagram

2.6 APSP Serial Input / Output (APSP-SIO)

The APSP Serial Input / Output is used to connect the APSP with front-ends, see Fig. 2-8. The communication is performed by TAXI links realized with AMD components Am7969/68-125. Two TAXI links transfer data from the front-end to the APSP-SIO to achieve a data rate of 22 Mbytes/sec. Data to the front-end are transfer via one TAXI link which give a data rate of 11 Mbytes/sec.

The APSP-SIO contains also 1 DSP processor TMS320C30 as Local Controller (LC) for flexible control of the APSP-SIO, e.g. housekeeping, TAXI I/O data management, DTN protocol handling, BIT, etc. The output of the TAXI Receiver are fed to FIFOs. The output of the FIFO are read by the LC via the Data Packer. The Data Packer handles different FIFO access modes to achieve optimal speed for data transfer, e.g. simultaneous read of both FIFOs and output of one 16-Bit word per LC access or double read of FIFOs and output one 32-Bit word per LC access.

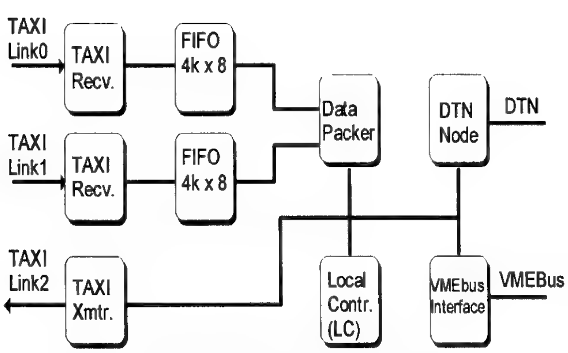

FIG. 2-8 APSP-SIO Block Diagram

3. APSP Software

All phases of the application development for the APSP are supported by a comprehensive set of tools, refer to fig. 3-1.

The aim of the **SYSTEM MODELLING PHASE** is the development of the processing algorithms. This is done on a Host platform (Sun, IPM PC) and supported by off-the-shelf mathematical and graphical SW-packages, like PV Wave from Precision Visuals.

In the **SYSTEM SIMULATION PHASE** an overall-simulation of the processing is required. The data driven simulation (e.g. PTOLEMY) fits best to the signal processing philosophy.

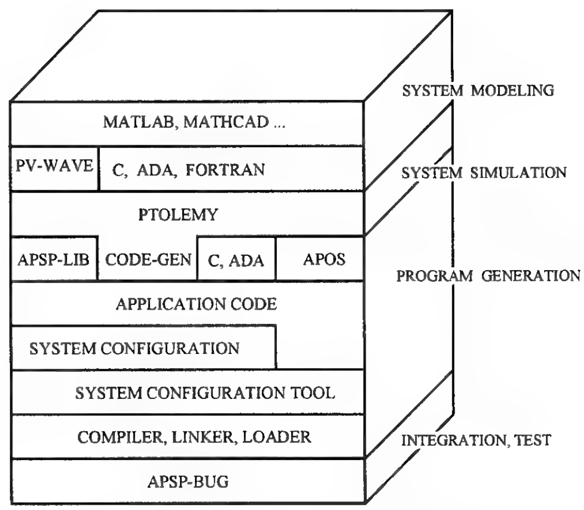

FIG. 3-1 APSP Software Environment

In the **PROGRAM GENERATION PHASE** the HOL algorithms are surrounded by APOS system calls. For time-critical sections APSP-LIB functions are inserted. The physical distribution of processes and data are managed by the System Configuration Tool.

INTEGRATION AND TEST is strongly supported by the APSP-BUG multi-processor debugger. It provides control and insight view to <u>each DSP</u> of the system.

3.1 Operating System

The APSP Operating System APOS is especially developed to meet the requirements of signal processing. It provides a low system overhead, fast

interrupt response time and short process switch time. Less than 300 words of the DSP's on-chip RAM are occupied by the OS.
APOS provides the following main objects for processing and communication:

- Mailboxes
- Processes
- Messages

The processing algorithms are embedded into **Processes.** Data are transferred as **Messages** between processes and **Mailboxes**. Processes are coupled by means of mailboxes. Each process has at least one input- and one output- mailbox. A process is activated by the scheduler, when its input-mailbox contains data. After processing, the results are stored in an output-mailbox. This activates the subsequent process(es).

All these features are especially useful for realising complex data distribution schemes. As indicated by Fig. 3-2 several connection schemes of processes and mailboxes are possible. For example a mailbox may be consumed by several processes, the data of several processes may be combined in 1 mailbox.

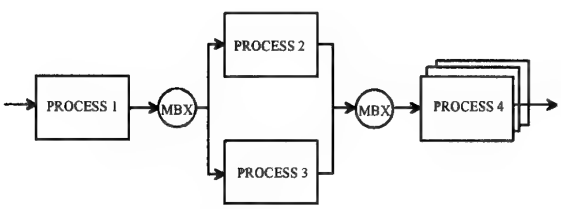

Fig. 3-1 Process Configuration Example

Such a communication scheme is independent of the process location. If the communicating processes are allocated on the same module, the mailboxes are realised as buffers in the module's memory area. If the processes are distributed among different hardware modules, the access to an off-module mailbox is routed automatically via the DTN.

3.2 System Configuration Tool Set

The multi processor characteristics of the APSP needs an extended support for system configuration and debugging.
For the definition of a process, the programmer generates a Process Configuration File which contains information concerning the allocation of code, data etc. This specification can be done in a high level syntax. **The Process Configuration Tool** takes this file and generates the corresponding linker command file.
In the Mode Definition File the allocation of processes to DSPs and the connection of mailboxes to processes are defined. This is done in a C-style syntax. The **Mode Configuration Tool** extracts the information from the Mode Definition File and generates the appropriate system tables for the APOS.

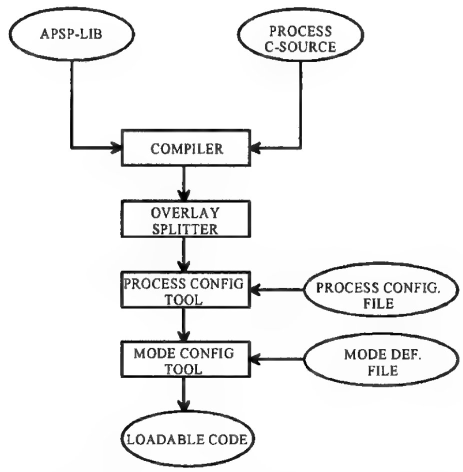

Fig. 3-2 Program Development Flow

The **APSP-BUG** is an essential tool for testing and integrating the application software. It offers the ability to observe and manipulate all memories and processors in the APSP system.
The Debugger is controlled from a Host computer (PC or SUN Sparc station) by means of a window oriented, menu controlled User Interface. Provisions on the processing hardware are made to generate system-wide breakpoints. When a processor reaches a breakpoint, all other DSPs in the system are halted. This freezes the current system state for analysis.

4. Implementation of Applications

4.1 Implementation Steps

The first step of implementing an algorithm on the APSP is to generate a simulation program in ANSI-'C' running on a general purpose host. For test and verification purpose synthetic or recorded flight trial data are used as input data.
The porting of the program to a single DSP system is done in the next step of the algorithm implementation. After verification of the real-time behaviour

of the processing, the time critical sections are replaced by off-the-shelf or proprietary optimised library routines.

In the final step the processing is allocated to the different processing modules of the APSP. Processes which are running on Processing Elements are extended by APOS system calls in order to implement resource sharing and inter processor communication functions.
Processes that are running on a Doppler Processor are modified by substituting the vector and FFT processing functions with appropriate sub-routine calls which utilise the FFT hardware.

4.2 Hardware Mapping of the Application

Three major APSP modules are involved in an example for a small performance solution, the so-called ISAR Processing Unit (IPU), refer to Fig. 4-1. This unit is used in an air maritime airborne surveillance radar for ship classification. It allows real-time processing of ISAR images with resolution of some meters and more then $2x10^5$ pixels.
The IPU gives a performance of 700 MFLOPS.

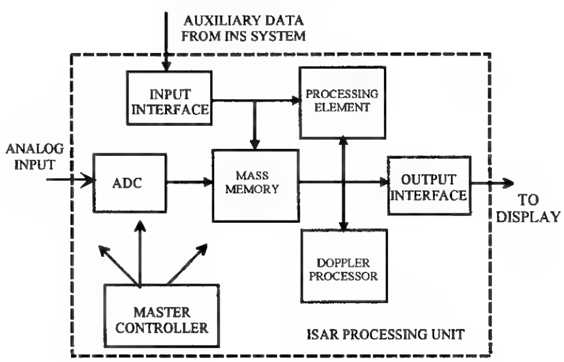

Fig. 4-1 ISAR Processor Unit

The involved APSP modules are:

The **Mass Memory** is used for buffering the incoming data stream from the Analogue/Digital Converter and for processing of intermediate results.
The **Doppler Processor** performs the ISAR pre-processing steps (Motion Estimation Motion Compensation and Prefocus), for algorithm details refer to [3].
The DSPs on the **Processing Element** share the data pre-processed by the DP and perform the image processing functions of the ISAR algorithm.

A challenging high performance application of the APSP is presented in Fig. 4-2. It shows the block diagram of a real-time SAR processor for medium and high resolution SAR imaging with up to $50x10^6$ pixels and one foot resolution. Digital pulse compression with high band-width-time product waveforms, range gate migration and curvature correction and autofocus require different types of data flow and processing.

The use of eight Doppler Processors reflects the intensive use of FFT processing for range and azimuth compression. The high need for memory function, which is typically for a sophisticated mapping mode, is met by Mass Memories with a total of 64 Mbytes in addition to the approximate 40 Mbytes memory capacity distributed over the SAR processor. The complete SAR processor consists of 20 boards and covers the processing requirements for four complete different SAR modes
The overall performance of the SAR processor is approx. 5 GFLOPS.

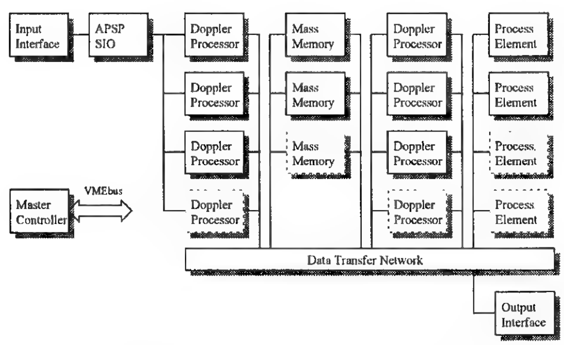

Fig. 4-2 SAR Processor Unit

References
[1] Texas Instruments, TMSC30C3x Users's Guide 2558539-9721, Revision J
[2] Sharp Electronics, LH9124 Users's Guide SMT90045 and LH9320 User's Guide SMT90048
[3] "Air Borne ISAR Processor for Ship Target Imaging" by D. Rapsilber; EUSAR'96

A SURVEY OF ADVANCED INFORMATION PROCESSING (AIP) TECHNOLOGY AREAS FOR CREW ASSISTANT SYSTEM DEVELOPMENT*

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Summary

In this survey, carried out within the framework of EUCLID RTP 6.5 CREW ASSISTANT project, the following, Advanced Information Processing (AIP) technology areas were surveyed: Software Engineering, Knowledge-Based Systems, Distributed Artificial Intelligence, Learning Systems, Planning, Model-Based Reasoning, Case-Based Reasoning, and Object-Oriented Databases. The survey evaluated the AIP technology areas with respect to the a predetermined set of criteria. The following criteria were used: Functionality Reliability, Performance, Modularity, Integration with other technologies, Engineering methodology, Maturity and next generation, and Availability within consortium. The main findings are: AIP technologies have a high degree of applicability in the A in general. The current state of the art in AIP technologies is at a mature level to offer acceptable solutions for the Crew Assistant development. It can be said that basically all of the AIP technologies investigated may be employed in some way in the CA development.

1. Introduction

This survey was prepared within the framework of EUCLID RTP 6.5 CREW ASSISTANT project under a contract awarded to a consortium consisting of Alenia, Bogaziçi Universitesi, DASA and NLR (SLIE) in the context of the EUCLID program under control of the CEPA 6.

The EUCLID CEPA-6 Crew Assistant (CA) programme is defined with the following objectives [1]:

1. Demonstrate that the concept of a crew assistant for military aircraft
   a) meets the needs of operational missions of the year 2000 and beyond, and
   b) improves mission capability in a cost effective manner;
2. Define a common European CA-concept;
3. Promote necessary Advanced Information Processing (AIP) techniques applicable to this CA-concept;
4. Establish a proper methodology for knowledge engineering among the European aerospace community in order to allow future joint production of Ca-systems.

The Crew Assistant (CA) program will combine traditional technologies with AIP technologies. Therefore a survey of the current state of the art of the AIP technologies was needed to provide a starting basis. This survey collects the feasible approaches as currently known and evaluates their applicability for the CA program

The AIP technology areas considered are:

- Software Engineering,
- Knowledge-Based Systems,
- Distributed Artificial Intelligence,
- Learning Systems,
- Planning,
- Model-Based Reasoning,
- Case-Based Reasoning, and
- Object-Oriented Databases.

* This work was supported partially by Turkish Ministry of Defense and by Boğaziçi University Research Fund (Project No:94A0108).

Paper presented at the AGARD MSP Symposium on "Advanced Architectures for Aerospace Mission Systems", held in Istanbul, Turkey, 14-17 October 1996, and published in CP-581.

2. Methodology for AIP technology survey

AIP technology survey was conducted in three main steps:

1. identification of technology areas to be evaluated and distribution among partner Industrial Entities (IEs),
2. determining evaluation criteria and a framework for evaluation,
3. evaluation of each technology area by the responsible IE.

The results of the evaluation of each technology area were combined to produce a recommendation for the CA development.

AIP technology areas to be evaluated were identified using a data form to collect proposals from partner IEs. The data form has entries specifying:

- the proposed area,
- relevance to CA,
- an indication of the importance of the area,
- evaluation criteria and techniques,
- estimated total effort needed for evaluation, and
- availability of expertise at IEs.

The evaluation framework is based on the identification of the issues implied by each criterion and the aspects of the AIP technology area relevant to the CA and to each criterion. It is assumed that the evaluation is a subjective evaluation expressed mostly in terms of a discussion of the relevant issues.

2.1 Evaluation criteria for AIP technology areas

The criteria used in the evaluation of the generic AIP technology areas include:

- Functionality,
- Reliability,
- Performance,
- Modularity,
- Integration with other technologies,
- Engineering methodology,
- Maturity and next generation, and
- Availability within consortium.

These criteria and evaluation with respect to these criteria are discussed below.

2.1.1 Functionality

Functionality relates the subject area of a particular AIP technology area to the functions of the CA application areas. Functionality is best expressed in terms of a matrix of CA application areas versus the capabilities / services provided by the AIP technology area. In this matrix, an entry shows that the particular AIP capability is applicable to the corresponding CA application area. Functionality is investigated at two levels:

- Applicability to CA in general
- Applicability to specific application areas in particular

Evaluation with respect to this criterion is done in terms of a discussion addressing the following issues within the context of the AIP technology area:

- List the functionalities of the AIP technology area (i.e., services/facilities provided by the area)

- Discuss each functionality, by giving a definition, and if relevant, by identifying the sub-functionalities
- Identify functions/requirements of the CA
- Make a matrix (i.e. a table) of CA functions versus functionalities of the AIP technology area, where an entry in the matrix denotes that the AIP functionality may be used in some way in the implementation of the CA function, and discuss relevant issues for each entry
- Give strong and weak points of the AIP technology area with respect to the criterion

2.1.2 Reliability

For each AIP technology area, the reliability criterion relates the reliability of the resulting CA to the particular AIP technology area used. Reliability is investigated in two dimensions:

- Verification, Validation and Certification (V, V and C)
- Impact on flight safety

From the point of view of reliability, V, V and C is related to whether there are proper V, V and C techniques/methods available to use for the particular AIP technology area, and if so, the impact of these techniques/methods on the reliability of the CA.

Evaluation with respect to this criterion is done in terms of a discussion addressing the following issues within the context of the AIP technology area:

- Identify those functions of the CA that are sensitive in terms of reliability
- Discuss the reliability of the CA, as a whole and at application area and functions levels, when a particular AIP technology area is utilized in the development of the CA
- Discuss techniques/methods of Verification, Validation and Certification (V, V and C) with respect to application areas and with respect to integration of V, V and C into the engineering methodologies to be employed

2.1.3 Performance

Performance of both the AIP technology area itself and the resulting CA are considered. Performance is investigated in two dimensions:

- Timeliness
- Real-time behavior

Timeliness is the time performance of the AIP technology area (i.e. the performance of techniques/methods used, tools available) or the CA developed. Timeliness is evaluated in terms of the speed of processing (i.e. fast or slow), bounded response time (i.e. response is guaranteed within a given limit of time), and any-time response (i.e. capability of having an answer at all times).

Real-time behavior issues include focus of attention and asynchronicity, etc.

Evaluation with respect to this criterion is done in terms of a discussion addressing the following issues within the context of the AIP technology area:

- Discuss in general time performance (i.e. speed of processing, bounded response time, guaranteed response, any-time response, etc.) of systems/applications employing the AIP technology area
- Discuss in particular at CA functions/requirements level the expected time performance of resulting systems
- Discuss/name the techniques/methods to achieve bounded response time, guaranteed response and any-time response from the AIP technology area
- Discuss in general real-time behavior (i.e. focus of attention, asynchronicity, etc.) and in particular techniques used for the AIP technology area
- Give strong and weak points of the AIP technology area with respect to the criterion

2.1.4 Modularity

Modularity is related to whether a particular system is composed of interacting modules. An AIP technology area

may or may not be able to support modularity. In other words, it may or may not be possible to develop a modular system, depending on the particular AIP area. Modularity has two very important implications on the resulting system:

- Scalability
- Maintainability

Scalability means the possibility of scaling up a small scale system without requiring to redo the work done for the small scale system. Scalability is related to economy in one hand and to ease (i.e. complexity) of system development on the other.

Maintainability is related to the ease of making changes and improvements in a system at the operation phase (i.e. while it is in use) of its life cycle. Maintainability is also an economy issue.

Evaluation with respect to this criterion is done in terms of a discussion addressing the following issues within the context of the AIP technology area:

- Discuss in general whether the particular AIP technology area supports (or, is suitable for) modularity and modular system development Identify the basic elements (i.e. components) used in defining modules
- Identify techniques/methods used in decomposing a large system into modules
- Discuss scalability issues (i.e. whether this is possible, how costly it is, etc.)
- Discuss maintainability issues (i.e. maintainability problems known, cost of maintenance, etc.)
- Give strong and weak points of the AIP technology area with respect to the criterion

2.1.5 Integrability

Integrability refers to the possibility of integration of an AIP technology with other technologies in developing a system. Integrability is related to modularity and the availability of modular components with standard interfaces.

Evaluation with respect to this criterion is done in terms of a discussion addressing the following issues within the context of the AIP technology area:

- Discuss in general the possibility and ease of integrating the particular AIP technology with other technologies
- If possible, discuss integration issues (e.g. architectural issues, communication and interfacing, need for developing new HW/SW modules, etc.)
- Give strong and weak points of the AIP technology area with respect to the criterion

2.1.6 Engineering methodology

Engineering methodology criterion has two aspects within the framework of AIP technology evaluation for CA development:

- Availability of an engineering methodology
- Impact on life cycle

Availability of an engineering methodology refers to whether there is a precise and well-defined set of techniques, methods and tools to use in developing a system using the particular AIP area. Impact on life cycle deals with the ways system development using the particular AIP technology affects the life cycle approach to system development.

Evaluation with respect to this criterion is done in terms of a discussion addressing the following issues within the context of the AIP technology area:

- Identify the availability of any engineering methodology applicable to the particular AIP technology area, giving a brief description of each of the available methodologies (i.e. overall approach, type of methodology, major steps or activities, main techniques, methods and tools, etc.)
- Discuss the implication of using a functional approach or an object-oriented approach in CA development with respect to the methodologies used for the particular AIP technology area
- Discuss how the engineering methodologies available for the AIP area would affect the life cycle of CA (i.e.

cost of system development, ease and cost of maintenance, etc.)

- Give strong and weak points of the AIP technology area with respect to the criterion

2.1.7 Maturity and next generation

Maturity and next generation are related to the state of the art of the particular AIP technology area.

Maturity can be expressed in terms of whether the AIP area is yet a research topic,. or a prototype system has been developed employing the particular AIP technology area, or there is an operational system available. Another indicator is the availability of commercial tools to support system development using the AIP area (i.e. tools implementing methods and techniques of the area or support tools).

Next generation refers to what can be expected from the particular AIP technology area in the (near) future.

Another criterion related to, maturity is embeddability (i.e. the embeddability into CA of a component developed using a particular AIP 'technology area -in other words whether it is possible with respect to hardware limits to embed a particular AIP technology into an aircraft as a hardware or software component).

Evaluation with respect to this criterion is done in terms of a discussion addressing the following issues within the context of the AIP technology area:

- Discuss the state of the art of the AIP technology area in terms of whether it is yet a research topic, or a prototype system is available, or an operational system is available, giving example systems if possible
- Discuss the availability of commercial tools to support the AIP technology area, if possible by naming and giving the main properties of the tools available
- Discuss if any major development is expected in the area in the near future
- Discuss the embeddability of a component developed using the particular AII' technology into CA (i.e. whether this is technically possible and feasible, whether there are already HW/SW available to embed such components into the aircraft as a CA module or component, etc.)
- Give strong and weak points of the AIP technology area with respect to the criterion

2.1.8 Availability within consortium

Availability within consortium is evaluated in two dimensions:

- Availability of expertise
- Availability of tools etc. related to the AIP technology area on the HW/SW platforms available within the consortium

Evaluation with respect to this criterion is done in terms of a discussion addressing the following issues within the context of the AIP technology area:

- Discuss whether expert knowledge is available within the consortium, stating where it is available
- Identify AIP technology area related tools within the consortium, giving main properties, platform on which it is available, etc. for each of them
- Give strong and weak points of the AIP technology area with respect to the criterion

3. Results of Evaluation

A summary of the evaluation of each of the AIP technology areas is given below.

3.1 Software Engineering Methodologies

Software engineering is the technological and managerial discipline for the systematic production and maintenance of software products that are developed and modified on time and within cost estimates [2]. Software . engineering is concerned not only with technological aspects but also with management problems.

Software engineering technology is at a mature state offering many alternative methodologies. The functional approach is well understood and well equipped. The object-oriented approach, although new, offers many advantages in modeling the real world, and in maintainable and reusable software development. It is expected that both approaches are to be used at different stages of the CA development.

3.2 Verification, Validation and Certification

Verification and validation of technologically advanced software (such as KBS, and AIP software in general) is often considered to be more difficult than V&V of traditional software. Nonetheless, the V&V process can be supported enormously by stepwise refinement of the requirements to the implementation and by documenting all steps taken. The need for correct requirements is of the utmost importance, and it should also be noted that requirements can (and often do) change during the development process [3].

The development process of Crew Assistant software, although it is to be developed for demonstration purposes only, should employ verification and validation fully at all stages of development.

3.3 Knowledge-Based Systems

As evidenced from existing CA programs, Knowledge Based Systems (KBS) is the most important AIP area in terms of the potential of use within the CA program. Therefore an investigation of knowledge-based systems is performed for the CA program. Expert Systems (ES) is another name used for KBS in a narrower sense, where in ES the knowledge base is formed using domain expert knowledge whereas in KBS knowledge may be obtained from other sources [4]. Most current applications of knowledge processing combine knowledge-based systems technology with other conventional methods to produce an overall solution to a particular problem.

Many functionalities of the Crew Assistant application are well suited to realize using the KBS technology. It can be said that the Crew Assistant is primarily a KBS application.

The KBS technology offers advantages in several dimensions in *the* Crew Assistant application:

In terms of functionality, KBS technology may be employed in all application areas chosen for the Crew Assistant. KBS are very reliable when compared with a human. Therefore KBS technology will increase the reliability of the aircraft-crew system. KBS offers reasonable performance for real-time applications. KBS technology offers modular design and development. KBS technology is integrable with other technologies. Integrability should be another important criterion in selecting KBS tools to be employed within the Crew Assistant program. Application development based on KBS technology is well suited for employing different engineering methodologies including the classical waterfall model and the prototyping model. There are many tools to support KBS technology, and human expertise is not scarce.

Therefore, it can be concluded that KBS technology satisfies all the criteria set for the evaluation of the generic AIP areas and, similar to the existing CA programs, it is expected that it will find several uses in this CA program as well.

On the other hand, it should be noted that some aspects of KBS technology, i.e. those areas that are the potentially weak points of KBS technology for the CA program, should be evaluated critically. Knowledge acquisition and assuring timeliness in real time are among these aspects. Performance should be an important criterion in selecting KBS tools to be employed within the Crew Assistant program.

3.4 Distributed Artificial Intelligence

The subject Distributed Artificial Intelligence (DAI) addresses distributed problem solving by multiple cooperative processing elements. It is concerned with issues of coordination among concurrent processes at the problem-solving and representation levels [5]. It differs from the more general area of distributed processing because it is concerned with distributing control as well as data and can involve extensive cooperation between entities. Distributed processing systems address the problem of coordinating a network of computing agents to carry out a set of separate and mostly independent *tasks,* as opposed to DAI. Distributed processing focuses on now bits of data can be physically moved among machines. So distributed processing or programming such as client-server are out of the scope of DAI.

Two categories of DAI research exist: parallel artificial intelligence and distributed problem solving (DPS). Parallel AI refers to a fine-grained efficiency-oriented approach, also referred to as connectionism. Neural networks are an example. DPS refers to coarse-grained (task-level) problem decomposition resulting in a number of expert or knowledge-based systems, generally called agents. Each of these entities include or exhibit some

intelligence, whereas parallel AI systems consist of entities that are relatively simple in construction and do not exhibit any intelligence, but the overall system exhibits some intelligence based on patterns of data processing of these fine entities (e.g. neurons in neural networks) [6].

The Crew Assistant application is primarily categorized as a system of cooperating expert systems for computer supported cooperative work. Crew Assistant is a complex application. The development of a Crew Assistant will already result in a complex system. DPS has a number of features to manage this complexity. Therefore; it is recommended to apply DPS technology in the Crew Assistant for the following reasons:

- modularity, reduced complexity and reduction life
- concurrent and incremental development,
- inherent distribution of the application (functional), integration of heterogeneous systems,
- reliability,
- easy mapping of task domains on agents,
- considers the limited availability of resources, '
- data abstraction,
- handling of bounded response times and reasoning, and
- real-time behavioral characteristics.

From a functional point of view, relating DPS to Crew Assistant Architecture as discussed in this section shows that blackboard systems and multi-agent systems are relatively made-to-measure technologies for Crew Assistant. These technologies can be applied to both element and system level.

DPS technology will increase reliability (and flight safety) of Crew Assistant if non-determinism is kept to an absolute minimum. Total flight safety is only guaranteed if the Crew Assistant's task is to *support* the crew, the. crew will always be in command as final *authority,* and delegated autonomous operation may only be considered for simple, routinely tasks that ensures deterministic and predictable agent behavior.

In order to achieve acceptable real time performance in DPS, the tendency is to let a multi-agent system form the backbone architecture of a Crew Assistant and to apply blackboard system technology to local problem solving (within an agent).

Decomposition of Crew Assistant by task domain and level of processing will form the basis for a modular system architecture of multiple cooperating agents. It allows for development and maintenance in a structured manner in order to be able to anticipate to the ever changing operational environment, aircraft systems and military demands.

DPS provides rich concepts far easy integration all kinds of methods and techniques, conventional as well as advanced information processing.

With respect to an engineering methodology, the heterogeneous aspect of DPS technology, system engineering should be a migration of conventional, object-oriented and knowledge-based system engineering methodologies with additional agent-specific and user interaction design features. It should allow for incremental development (prototyping).

The potency of DPS technology, blackboard systems as well as multi-agent systems, is recognized in the aerospace community. A rich set of tools is already available. Prototype and operation real-time applications

Because of the nice features of DPS and the progress in research, tools, applications and multi-processor technology that is currently being made, it can be concluded that DPS systems based on multi-processor technology will play a dominant role in next generation advanced information processing technologies.

On the other hand, the overall complexity of applying DPS to Crew Assistant should not be underestimated. In order to control complexity as well as to achieve the required performance, decomposition, distribution and. cooperation strategies should not be too flexible. In that sense, the following measures can be taken for CA development:

- develop the CA incrementally (range of prototypes) to increase functionality and performance step by step
- provide a good development environment (an advanced DPS toolkit is required)
- apply decomposition on basis of a formally prescribed task hierarchy

- a priori known distribution of tasks among agents
- avoid conflicts between agents
- design a fixed community-like organization of agents with strict rules of behavior based on identified task domains (functionally decomposed agents such as mission planning, situation assessment, etc.).
- reduce non-determinism,
- make use of next generation on-board hardware resources based on multi-processor technology
- do not include explicit redundancy as a main objective in the CA in order to manage complexity and to focus mainly on functional problem solving. Nevertheless, a secondary design goal should be to meet future reliability requirements and should be taken into account.
- apply resource management.

In conclusion, it is recommended to apply DPS technology in Crew Assistant and let it be a driving technology for the overall Crew Assistant architecture.

3.5 Learning Systems

Most KBS are hand-built systems without any learning capability. Whenever necessary, they are modified manually. Although such systems appear to be simple there are inherent difficulties associated with them [7], [8].

- **Difficulty of assuring completeness and correctness of knowledge bases**. It is generally assumed that the knowledge base of hand-built KBS is complete and correct. However, for most real world tasks, achieving completeness and correctness are extremely difficult, if not impossible.
- **Increased time complexity**. Making a knowledge base as complete and as correct as possible may entail writing thousands of interacting, possibly recursive, rules. Using such rule sets may be very demanding in real time applications.
- **Difficulty of modifying knowledge bases**. As interactions increase in a rule set, it becomes difficult to predict all of the changes resulting from modifying a single rule.

Therefore, a mechanism of automating knowledge introduction to the KBS is necessary. It is possible, in principle, to achieve this by making the system capable of learning.

With respect to inductive learning, if noisy data is present it is highly probable that the knowledge base will not be consistent and complete. The time complexity of inductive learning algorithms does not allow them to be used in real time applications. Also, the requirement of verification and validation requires them to be used off line. Inductive learning may be used to generate or augment the knowledge bases of the KBS to be used in the CA.

Genetic algorithms (GA), on the other hand are used for . combinatorial and parameter optimization. Although they have the ability to locate the global optimum, depending on the control parameters, the possibility of being trapped in a local minimum exists. GA do not have a reliable, bounded convergence time for the global optimum. However, they have the graceful degradation property, they always present solutions that improve over time. GA allow modularity but they are not scaleable. There is not an established methodology for designing a GA application.

Other than learning, artificial neural networks (ANN) are also used for classification, and function approximation, i.e., time series forecasting, control etc. Current methodologies of training neural networks do not allow them to be used on-line. For this reason, training should be carried out off line. Once trained, an ANN can perform prediction in real-time. However, after each mission; data gathered during mission can be used to improve the ANN used in the CA, thus allowing it to adapt to changing situations, enemy vehicles, etc. ANN are at least as reliable as other classification systems, if not more.

To summarize, learning can be used in the CA in two stages:

- In the initial construction of the rule based knowledge bases such as in self-defense and mission planning application areas, and
- In the maintenance of the above mentioned knowledge bases.

For the initial construction, inductive learning or genetics based learning will be more appropriate, as these methods produce symbolic output. However, during the maintenance phase, all of the three learning methods can be used. Although, ANN are marginally better than the other two methods, re-extracting symbolic knowledge

from the ANN structure after beaming is a costly process.

It is also expected that ANN will be used for classification and recognition tasks based on low level data, such processing environmental data or systems/malfunctions data that may also amount to sensor fusion.

3.6 Planning

In a CA, one fundamental AIP problem is to deal with a set of variables belonging to the real world domain and with a set of possible actions, in order to determine the sequence of actions allowing to reach the current goal. This is a typical planning problem (9) because the system has to generate a sequence of actions that will achieve given goals in a domain complex enough that the appropriateness and consequences of the actions depend upon the world states in which they are to be executed. In particular, the planning system must keep track of and reason about differing world states at different point in time. This feature distinguishes the planing problem from similar problems such as ' scheduling. In fact, in scheduling, the problem is to assign resources in order to carry out a plan without requiring that the system reason about how the world changes as scheduled events occur.

Planning is still a research area. There is not a single operational planner that can solve all the problems of planning (especially in real time) and there are no commercial tools available for planning.

The applications realized in literature seem to be on quite easy problems, with real constraints not being very strict. Although the modem planners seem to be able to cope with most of the problems of planning (non linearity, real time etc.) as they are all based on the search on the state space, there is a need for paying attention. In the CA, planning can provide significant improvement in the quality of help that the system can offer to the pilots, providing a new plan as the modification of the current plan as required by the changes in the external situation.

Due to the difficulties and the technical risks inherent to these technologies it is recommended to pay great attention to the planner architecture and to develop the CA in a scenario of realistic dimensions. This is to verify that the system can really cope with the real time problem.

3.7 Model-Based Reasoning

Model based reasoning is a sub-field of artificial intelligence oriented to device representation. The word "model" means "a decomposition of a real-world .device into components which captures *the* structure of the device and its components, and the way the components' actions give rise to the device's actions as a whole" [10]. The model based approach, compared with the traditional artificial intelligence approach, is a step forward in many ways. Traditional artificial intelligence approaches usually rely on heuristic knowledge elicited from a human expert. This allows the realization of systems that exhibit a very good agreement with the experts. On the other side, there are strong limitations in terms of performances, flexibility, explanation capability. The model based approach allows to overcome such limitations, because model based systems are largely device-independent, more easy-to maintain, built with re-usable component models, and o their explanation capabilities are built-in. Moreover; they overcome the difficulties of dealing with new devices, on which there is ml expertise available, and shows a graceful degradation of performances at the boundaries of the domain knowledge, where traditional systems usually simply stop working.

The model based approach is suitable for applications where it is necessary to represent complex devices whose behavior must be simulated and monitored (for instance, with diagnostic purposes). With such an approach, it is easier to cope with *the* complexity of the Crew Assistant application. It may be difficult to attain the required real-time performance, unless other types of knowledge (associational, procedural, etc.) is incorporated in the system. However, such an integration could raise difficulties, in maintaining the overall consistency of the knowledge embedded in the system. Moreover, with *the* present state of the art, it is not possible to guarantee the reliability of such an approach. Therefore, the model base reasoning should be considered only as a supporting approach.

On the other hand, a model based representation is clear, easy to maintain and to extend. It is suitable for an easy implementation of graphical development tools and reusable component libraries. The system can be incrementally developed, making it possible to check and to understand the needs and problems better at each step.

Currently, there are no powerful commercial tools available. Nevertheless, *the* technology is mature enough. Some companies seem to have achieved very good results. It is. expected that they will commercialize their tools soon.

3.8 Case-Based Reasoning

Computer systems that solve new problems by analogy with old ones are often called Case-Based Reasoning (CBR) systems [11]. A CBR system draws its power from a large case library, rather than from a set of first principles alone. Essential to the success of a case-based system is the development of a rich-set of indexing mechanisms by which cases are built and retrieved. The case-based paradigm can be used for building intelligent agents that use heuristic knowledge, first principles as well as special-case knowledge from previous experiences.

Case-based reasoning is a cognitively plausible model of reasoning and a method for building intelligent systems. It is grounded in .commonsense premises and observations of human cognition and has applicability to a variety of reasoning tasks, providing for each a means of attaining increased efficiency and better performance. Case-based reasoning integrates problem solving, understanding, learning and memory into one framework. .

The CA application is primarily categorized as a system of cooperating expert systems for computer supported cooperative work. The development of a CA will result in a complex system. For the implementation of one or more of these cooperating expert systems CBR might be a reasonable approach.

3.9 Object-Oriented Databases

The Object-Oriented Databases technology was developed over the last 5 years as a mix of the programming methodologies based on the object-oriented approach and the more traditional database techniques aimed to allow an efficient and reliable management of persistent data [12].

By introducing not only the persistency but also other key features (such as secondary store management, concurrency control, recovery capabilities, access facilities etc.) into a paradigm targeted on improving software reliability, reusability, modularity and adherence to the reality, the OODB have done a major step toward the unification of the programming and data management technologies.

Since this achievement can be exploited at its best when the system to be developed must deal with very complex data (where complexity is meant both in terms of structure and interactions), the Crew Assistant project seems particularly suitable to take advantage of its benefits, as this will result in an efficient and productive development of reliable, reusable and highly modular software.

Object-oriented database technology is in accordance with all the software engineering requirements (modularity, performance, integrability, etc.)

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Nouvelles sources de Données Géographiques pour l'Aide à l'Identification Air-Sol

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1. INTRODUCTION

Pour les missiles de croisière et les avions à long rayon d'action, des données géographiques ont été utilisées très tôt pour des fonctions de navigation comme le recalage de navigation et la navigation très basse altitude. Pour le recalage de navigation deux types de données ont été utilisées : des données de relief (DEM : Digital Elevation Model) ou des données topographiques (landmarks ou amers) ; pour la navigation très basse altitude : essentiellement des données de relief. Le développement des satellites d'observation à partir des années 70 a permis de constituer assez rapidement des bases de données de relief importantes ; la constitution de MNT (Modèle Numérique de Terrain) à partir d'un couple stéréoscopique est largement automatisable et nécessite donc peu d'intervention de l'opérateur ; d'autre part on peut penser que sur des surfaces assez étendues le relief est une information assez stable dans le temps et qui peut donc être préparée assez longtemps à l'avance contrairement aux données planimétriques (cultural features) de nature plus éphémère. Ceci a donné naissance aux données DTED (Digital Terrain Elevation Data) qui se présentent sous la forme de données maillées correspondant à des pavés de 3 '' x 3'' d'arc (soit une maille d'à peu près 60 m x 90 m à la latitude de 45°). Les données planimétriques du type DFAD (Digital Features Analysis Data) se sont développées de manière plus inégale que les données DTED et leur qualité est probablement plus variable car leur saisie ne peut être complètement automatisée et comporte donc une part d'interprétation tant dans la sélection des éléments que dans le tracé retenu (généralisation). D'autre part le DFAD avait au départ une couverture limitée, principalement le théâtre Centre-Europe. Or les théâtres d'opérations sur lesquels ont été utilisés ces dernières années les avions d'arme, sont extérieurs à cette zone (Falklands, Bosnie, Irak, Burundi, ...).

Dans un premier temps, principalement destinées à l'aide à la navigation radar, ces données privilégiaient les éléments topographiques susceptibles de produire des données relatives aux échos forts (c'est ainsi que seuls les tronçons d'axes routiers sur talus pouvaient être sélectionnés car seuls donnant des échos forts). Puis devant le développement des systèmes de commandement la vocation « échos forts » s'est étendue pour donner une représentation topographique complète de la zone. Les fichiers à vocation militaire se sont alors rapprochés des données du domaine civil.

Le développement des systèmes d'information géographiques civils ou militaires (SIG/GIS), des systèmes d'information et de commandement militaires (SIC/C2I/C3I), des simulations et des jeux de guerre a poussé à la constitution de bases de données nouvelles plus précises, de couvertures toujours plus étendues. Ces bases de données peuvent être utilisées pour les fonctions de recalage de navigation sur de grandes étendues comme pour le missile de croisière APACHE sous maîtrise d'oeuvre MATRA-DEFENSE et dont THOMSON-CSF réalise précisément le Radar de Recalage et de Détection. Mais ces bases de données peuvent aussi, comme on va le montrer, être utilisées pour l'Aide à l'Identification d'Objectifs dans les missions Air-Sol. En effet, même si pour ces missions, le pilote dispose généralement d'une vue capteur sur laquelle il peut désigner la cible par ses propres moyens, il est intéressant d'automatiser au mieux les phases de reconnaissance et d'identification pour que le pilote n'ait qu'à confirmer la désignation qui lui est alors proposée par le système et se concentrer sur le choix du point d'impact.

Dans le but de montrer comment peut se présenter cette aide, la présentation aborde alors les points suivants :

- quelles données géographiques et sous quelles formes peuvent faciliter la tâche du pilote ?

- ces données existent-elles (avec un panorama sur les données en projet) ?

- exemples d'utilisation de ces données pour l'Aide à l'Identification.

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2. AIDE A L'IDENTIFICATION AIR-SOL ET DONNEES GEOGRAPHIQUES

Quel peut-être l'apport des sources de données géographiques dans le cadre des missions air-sol et, plus particulièrement en ce qui concerne l'aide à l'identification ? La notion d'identification air-sol est considérée ici au sens large du terme, à savoir comme ensemble de phases de détection, de localisation ou d'identification proprement dite de la cible ou de l'amer considéré. La cible peut elle-même entrer dans deux catégories distinctes. La première est celle des cibles fixes, par exemple les superstructures (routes, ponts, bâtiments) ; la deuxième concerne les cibles en mouvement et les cibles déplaçables

Dans un cas comme dans l'autre, l'identification s'appuie sur l'utilisation de données de référence élaborées en préparation de mission, et qui se rapportent suivant les cas à la cible elle-même ou à son environnement. Ces données permettent une analyse en cours de mission de l'image fournie par un capteur optronique embarqué afin de fournir des indications sur une zone de présence probable de la cible, puis sur l'identification de la cible lorsqu'elle est détectée et localisée.

L'apport potentiel des sources de données géographiques se situe au niveau de la création de données de référence. Considérons tout d'abord le cas des données « classiques », de type carte géographique ou photographie satellitaire (SPOT).
La phase de recherche de la zone de présence probable de la cible peut s'appuyer sur ce type de données qui renseignent sur la présence et la position des superstructures à rechercher dans l'image courante, et qui permettent de délimiter la zone d'intérêt. Cette étape est menée à bien à un niveau global et concerne l'environnement de la cible. Une grande précision de localisation n'est pas nécessaire.

Les limitations des données géographiques « classiques » apparaissent dans les phases de localisation précise et d'identification de la cible elle-même. Les deux catégories de cibles présentées plus haut ouvrent sur deux types de besoins nouveaux.

Les cibles fixes (superstructures, bâtiments, ...) sont la plupart du temps présentes dans des données géographiques classiques. La limitation vient dans ce cas de la précision ou du type de représentation.

Prenons l'exemple d'une route, qu'elle soit la cible elle-même ou un élément servant à la localisation précise d'une cible. Une carte géographique, du fait de la représentation schématique adoptée, ne permettra pas de la localiser précisément, tant qu'aucune donnée réelle sur sa largeur ni d'ailleurs de son tracé précis ne sont connues.

D'autre part, la localisation précise et l'identification des cibles fixes rendent nécessaires la disponibilité d'informations de précision métrique qui ne peuvent pas être fournies dans les sources classiques (peut-être cependant avec des satellites de la classe HELIOS ou de la nouvelle génération commerciale qui voit le jour aux Etats-Unis).

Le cas des cibles mobiles et des cibles déplaçables est différent, puisqu'aucune information concernant leur position précise n'est connue en préparation de mission. Les sources de données classiques qui se limitent à des informations de type géométrique ne sont donc pas exploitables, en dehors de la détermination d'une zone de recherche. Seules des informations de contexte pourraient éventuellement guider les phases de détection et d'identification de ce type de cible.

Ce constat pourrait paraître assez pessimiste en mettant en évidence notamment les points suivants :

- la relative pauvreté des données dont on peut disposer en Préparation de Mission au vu des résolutions très grandes obtenues avec les caméras de bord ; ceci est particulièrement vrai pour des théâtres extérieurs mal cartographiés ;
- l'inadaptation d'une source de données d'échelle géographique fixe alors que sur l'image avion il peut y avoir des rapports d'échelle de 1 à 10 entre le haut et le bas d'image ;
- la schématisation des objets des bases de données géographiques qui les rend difficilement reconnaissables sur les vues obliques en basse altitude ;

Pourtant, lors des opérations aériennes de la récente Guerre du Golfe, des statistiques intéressantes ont été établies sur la probabilité pour le pilote d'identifier sur une image sa cible à coup sûr en ne disposant comme référence que de la carte topographique de la zone et des coordonnées de la cible ; d'après certaines analyses cette probabilité s'élèverait, dans de nombreux cas, à moins de 50% à la première passe. L'utilisation d'une image type SPOT convenablement mise en perspective, une des techniques présentées ici, semble avoir augmenté de manière considérable les chances de tir réussi au premier rendez-vous. Il n'existait que peu de fichiers géographiques vecteurs sur l'Irak aussi les images SPOT ont-elles été intensément utilisées ; il est certain que la disponibilité de fichiers vecteurs aurait pu aussi

conduire à un bon pourcentage de tirs réussis dès la première approche.
Les images suivantes illustrent l'intérêt, mais aussi les limites de l'utilisation des images SPOT pour l'aide à l'identification par le pilote.
Dans un premier cas on compare une vue aéroportée (en haut) avec une vue SPOT mise en perspective (en bas) pour paraître à peu près sous les mêmes conditions de prise de vue. On constate que la corrélation visuelle entre les deux images est facile (d'autant que l'angle de site élevé de la prise de vue minimise les distorsions).

Des différences apparaissent au niveau des bâtiments dont l'élévation n'est pas prise en compte dans la mise en perspective SPOT et dans la différence d'occupation des quais (les images n'ayant pas été prises à la même date).
Néanmoins si le pilote dispose de la vue basse calculée à partir d'une image SPOT téléchargée et des conditions inertielles courantes, cela doit lui permettre de passer rapidement en petit champ sur l'objectif qu'il aura localisé facilement et alors de procéder à l'identification.

Dans le second cas, la scène est plus complexe et il y a moins d'amers prédominants. L'image du haut est un extrait d'une image aéroportée ; celle du bas est obtenue à partir de la rétroprojection d'une image SPOT. La scène est à plus basse altitude que la précédente.

Les contrastes n'étant pas les mêmes entre les images, la corrélation automatique est plus difficile; contrairement à la vue précédente, il y a plus de possibilités d'appariements entre les éléments rectilignes ce qui complique la validation rapide de la corrélation automatique proposée. Il est alors préférable d'utiliser comme référence des fichiers d'objets géographiques comme on va le voir.

3. DONNEES GEOGRAPHIQUES POUR L'AIDE A L'IDENTIFICATION AIR-SOL

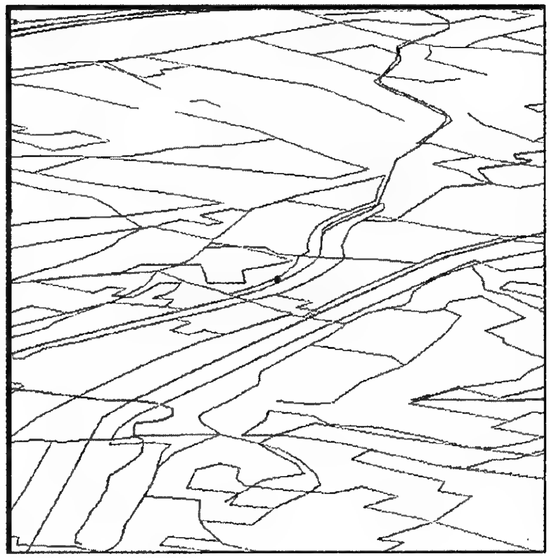
Seront disponibles à terme pour être utilisées dans des missions d'attaques d'objectifs au sol et pour remplacer ou compléter les données DLMS, les trois classes de données suivantes dont des exemples sont présentés :

- données hectométriques (DCW: Digital Chart of the World ; couverture mondiale ; échelle adaptée aux cartes au 1/1 000 000 ou moins) ;
- données décamétriques (VMAP : Vector Map ; couverture mondiale ; souvent présenté comme le successeur du DLMS/DFAD ; échelle adaptée aux cartes au 1/100 000) ;
- données métriques (type BD Topo de l'Institut Géographique National en France) ; précision de classe métrique ; la constitution de telles bases de données est onéreuse et la couverture mondiale ne se fera sans doute que très lentement ; par contre la croissance du marché des images satellitaires et la mise sur le marché de systèmes de restitution photogrammétrique à faible coût permettront probablement de réaliser des fichiers sur des petites zones dans des conditions opérationnelles raisonnables de coût et de délai.

Les deux images ci-contre illustrent ces deux derniers types de données sur la même région. Le point de vue choisi pour la mise en perspective des images, le même pour les deux vues, est une distance capteur /centre image de 20 000 m, une altitude de 5 000 m et un champ carré de 4° x 4°. Sur chacune des images seuls les objets appartenant aux quatre thèmes : cours d'eau, réseau routier, réseau ferré, limites de végétation sont représentés à des fins de comparaison.

Avant d'analyser plus en détail l'intérêt représenté par chacun de ces trois types de données, on peut tirer de leur comparaison les informations suivantes:

- les données DCW ne sont généralement pas assez riches (sauf dans le fond d'image à faible site) pour faciliter la reconnaissance ;
- les données type VMAP permettent un bon quadrillage de la zone ; en bas d'image la représentation est toutefois un peu schématique ;
- les données du type BD Topo peuvent paraître trop riches pour ce type d'échelle ; il serait en effet très difficile de faire de la corrélation automatique image et carte projetée avec cette densité d'éléments ; cependant au moins dans la partie basse de l'image la précision géométrique est bien celle exigée par le champ et la résolution de l'image ; seuls certains éléments doivent donc être sélectionnés pour entrer dans des programmes de recalage automatique.



Type VMAP

Type BD Topo.

L'intérêt potentiel de fichiers de données géographiques étant reconnu encore faut-il pour en tirer un bon parti respecter certaines conditions d'emploi.

Comme on l'a déjà souligné deux problèmes majeurs se posent :

- les règles de saisie des éléments qui figurent dans les fichiers géographiques ne prennent pas en compte la visée oblique et cherchent plutôt à avoir une représentation homogène en visée verticale ; ceci complique beaucoup l'utilisation de tels fichiers en vue très oblique puisque l'échelle entre le haut et le bas d'image n'est pas du tout la même (le rapport d'échelle pour une hauteur de vol de 600 m, une portée de 15 000 m et un champ de 4° est supérieur à 10) ; les éléments seront très denses dans le fond d'image et très clairsemés dans le bas d'image ;

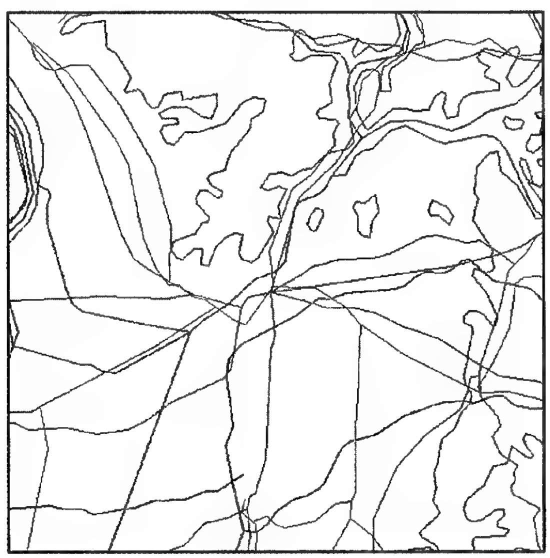
- les contraintes de représentation des fichiers géographiques vecteurs ne sont pas particulièrement orientées vers la lisibilité cartographique ; ainsi la voirie pourra être représentée par les axes des voies plutôt que par les bords qui sont pourtant plus visibles que l'axe sur l'image. D'autre part il n'y a généralement pas de contrainte sur l'épaisseur des traits ou des objets qu'ils délimitent. Les parties masquées peuvent aussi n'être pas totalement respectées.

Malgré ces défauts les données géographiques vecteurs peuvent être une source précieuse d'informations dans l'aide à l'identification Air-Sol.
Pour le montrer on a considéré plusieurs sources de données sur la même zone et après les avoir comparées en vue oblique, on les a comparé en vue verticale ici..

Les données présentées (à l'exception du DCW) sont issues d'un jeu d'essais mis gracieusement à disposition d'industriels à fin d'expertise par l'Institut Géographique National Français.

Les sources de données sont sur la même zone et représentatives des futurs produits VMAP et autres produits à plus grande échelle.
La même zone est représentée en vue verticale à la même résolution (sauf le DCW) pour juger des densités respectives.

Les sources de données sont les suivantes :
- DCW, Digital Chart of the World
- BD Carto de l'IGN, échelle approximative du 1/50 000 (représentative du VMAP)
- BD Topo de l'IGN, échelle approximative du 1/15 000.
Ces deux dernières BD ont naturellement pour vocation de couvrir le territoire français.



Au vu de ces différents fichiers, il est tentant de réaliser des images prédites qui soient un hybride de ces différentes sources de données (dans la mesure où ces différents fichiers sont disponibles) : dans le fond utilisation du DCW ou VMAP et dans la partie basse de l'image utilisation de VMAP ou type BD Topo. Un exemple d'une combinaison des données type VMAP et type BD Topo est montré sur la figure ci-dessous dans les mêmes conditions de prise de vue que pour les trois vues précédentes. La densité des éléments représentés est plus homogène sur l'ensemble de l'image. Les raccords ne sont pas parfaits car la précision n'est pas identique pour les différents fichiers. Cela ouvre pourtant la porte à la réalisation de compositions originales dans lesquelles la densité sur l'image est à peu près constante.

La source de données géographiques qui apparaît la plus appropriée tant au point de vue de la couverture, de la précision requise (du moins pour l'Aide à l'Identification) que de la disponibilité semble bien être la source VMAP. Un problème risque pourtant de se poser avec ce type de fichiers (comme il s'est d'ailleurs posé avec les données DFAD/DLMS) : la variation de qualité avec les zones ; les règles de fabrication permettent en effet difficilement de s'assurer que la qualité est homogène en couverture et en précision sur toute la zone couverte.

Il est possible aussi d'envisager pour ces fichiers des modes de représentation qui soient plus adaptés à la reconnaissance aérienne qu'ils ne le sont maintenant: par exemple pour des voies de largeur non négligeable, préciser le tracé des bords plutôt que l'axe. Des efforts sont aussi à faire en préparation de mission pour sélectionner suivant l'axe de vol la bonne densité d'éléments en fonction de la profondeur. Ce point, comme il sera montré dans le chapitre suivant, est crucial pour une bonne réussite des algorithmes de recalage automatique.

4. EXEMPLE D'UTILISATION DE DONNEES GEOGRAPHIQUES DANS L'AIDE A L'IDENTIFICATION AIR-SOL

Un des objectifs de l'aide à l'identification est de désigner automatiquement au pilote la cible dans l'image lors du premier passage de l'avion. Pour contribuer à cette mission THOMSON-CSF a développé un algorithme utilisant les données géographiques.

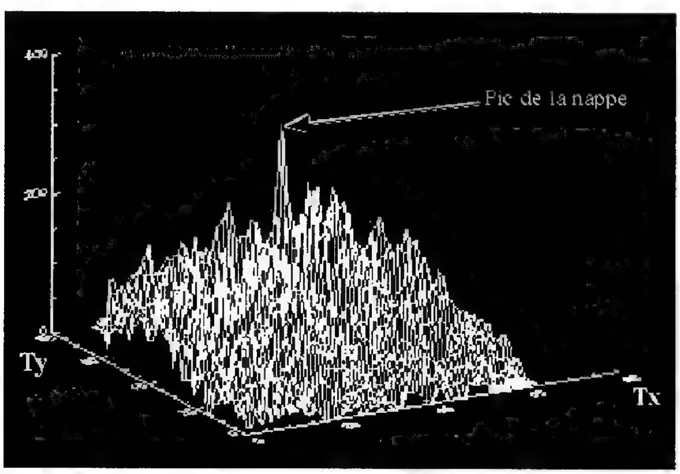
Quand l'avion atteint la position estimée pour laquelle la cible est dans le champ de vision l'algorithme capture une image et en extrait les éléments caractéristiques. Ces éléments doivent être comparables aux données géographiques disponibles. Dans le cas d'attaque de sites comprenant des superstructures, l'utilisation de segments de droite présente plusieurs avantages :

- tout d'abord, ils sont directement en adéquation avec les données du modèle qui sont classiquement représentées sous forme de vecteurs,
- ensuite, il existe plusieurs techniques d'extraction de segments qui présentent de bonne probabilité de détection et une faible fausse alarme;
- enfin une bonne présence de ces éléments dans toute l'image.

L'identification de la cible repose sur la mise en correspondance entre les segments extraits de l'image et ceux d'un modèle tel que présenté dans le paragraphe précédent. En fonction des paramètres de la mission (incertitudes sur les paramètres de vol, distance d'acquisition, champ du capteur, ...) la projection du modèle à partir des données inertielles de navigation présente principalement des erreurs de translation; les distorsions sont faibles et peuvent être négligées en première approximation. On peut envisager deux approches pour retrouver la position exacte d'un modèle projeté dans une image :

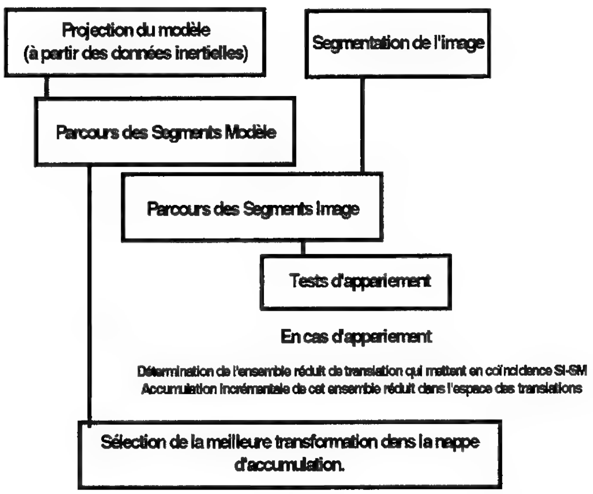
1. La première regroupe des méthodes 'descendantes' de l'ensemble des solutions vers l'image. Ce sont des approches du type corrélation où l'on teste toutes les positions possibles en associant à chacune un coût de superposition. La position correspondant au coût le plus faible fournit la position du modèle. Ces méthodes peuvent se combiner avec des approches pyramidales où l'on choisit différentes possibilités de recalage à de faibles précisions, solutions que l'on affine et distingue à de meilleures résolutions.
Ces méthodes demandent la mise au point de fonctions de coût discriminantes qui sont souvent coûteuses en temps de calcul. De plus beaucoup des solutions testées correspondent à des recalages image/modèle impossibles et il faut posséder le résultat de la fonction de coût pour les éliminer.

2. L'autre catégorie, comprend les méthodes 'montantes' de l'image vers l'ensemble des solutions. On pense ici aux méthodes par accumulation où la solution se détache progressivement en accumulant des informations locales. Une information locale correspond ici à une hypothèse de déplacement superposant un segment modèle avec un segment image. En représentant toutes ces transformations dans un espace approprié on obtient par effet de vote la solution qui recouvre le plus d'éléments du modèle sur l'image.
Dans le cas où la transformation à identifier est une translation, l'espace d'accumulation est de dimension deux suivant les axes image et forme ce que l'on appelle couramment une nappe d'accumulation.
La figure suivante présente un cas typique de nappe d'accumulation vue en 3D.



Opérationellement la sélection du pic le plus haut n'est pas toujours suffisante pour déterminer la bonne solution avec la meilleure précision. C'est pourquoi la détection du bon pic est associée à un critère de qualité dépendant localement de la nappe d'accumulation et des segments appariés.

Pour l'application considérée, THOMSON-CSF a retenu une méthode accumulative dont un organigramme général est donné figure suivante.



Organigramme de la méthode accumulative.

Le nombre et la qualité des hypothèses accumulées sont des facteurs fondamentaux pour le bon fonctionnement de ce type de méthode. En effet toute hypothèse erronée bruite la nappe d'accumulation et fragilise la recherche d'une solution globale. C'est pourquoi on utilise classiquement des critères de comparaison géométrique entre les segments image et modèle pour former les hypothèses locales les plus probables avant de les accumuler.

L'utilisation de données géographiques permet en préparation de mission de constituer des modèles dont les caractéristiques peuvent améliorer l'identification. Il est toujours difficile d'établir des règles de sélection exhaustives. Cependant on peut retenir quelques règles simples.

Il paraît en particulier intéressant de sélectionner des éléments longs, car la probabilité qu'un tel segment extrait dans l'image soit du bruit est faible. Il est également important de disposer de segments dans différentes classes d'orientation. On peut aussi s'intéresser à la répartition des éléments dans la scène en s'assurant d'une certaine homogénéité ou au contraire en favorisant des structures caractéristiques (noeud routier, ...).

Enfin, si l'on a une connaissance suffisamment précise de la configuration d'attaque (cap d'arrivée, distance, altitude, ...), on peut sélectionner les éléments en fonction de la résolution du pixel dans l'image. Par exemple pour l'arrière plan on ne retiendrait que les éléments aux dimensions les plus importantes (par exemple les berges comme limites d'un fleuve). A l'opposé pour le premier plan on retiendrait des éléments de dimensions plus faibles définis avec une bonne résolution.

Du point de vue opérationnel ces critères de sélection (géométriques, topologiques, ...) peuvent être automatisés.

Un dernier apport des nouvelles données géographiques serait d'associer aux primitives des attributs. On disposerait ainsi de critères de sélection supplémentaires comprenant par exemple la visibilité (géométrique, radiométrique) ou leur aspect dans l'image. Par exemple dans le cas des segments, la connaissance du sens du contraste quand elle est disponible et pertinente, dans les cas de transition eau/terre par exemple, peut éviter des erreurs de recalage.

Les figures suivantes présentent un exemple de recalage pour l'aide à l'identification d'objectif sur une zone portuaire.
La première image présente le modèle embarqué projeté à partir des conditions inertielles. Ce modèle a été constitué en préparation de mission à partir de fichiers géographiques en utilisant des heuristiques de sélection.
Les traits rouges correspondent aux segments extraits sur l'image, les segments superposés en vert représentent les éléments du modèle projetés à partir des données inertielles.
La seconde image présente le résultat du recalage en translation du modèle sur l'image.

Modèle initial et segments extraits.

Modèle recalé et segments extraits

Après cette étape, le pilote peut passer aux phases suivantes de l'identification.

5. CONCLUSION

L'information géographique dont il a été principalement parlé dans cet exposé est de nature géométrique ou sémantique. On a vu son intérêt et son utilisation pour l'aide à l'identification automatique d'objectifs. On a également présenté des approches spécifiques pour la constitution des modèles embarqués en particulier par l'utilisation conjointe de fichiers géographiques avec des résolutions différentes ou encore par la mise en place de critères automatiques de sélection.

Peu a été dit sur les propriétés de rayonnement électromagnétique des objets qui sont pourtant si sensibles au niveau des capteurs infrarouge ou autres. Cette information n'apparaît pratiquement pas dans les nouveaux fichiers de données géographiques. Pourtant, on a vu qu'à l'origine ces propriétés étaient à la base même de la leur constitution. Bien que délicate à maîtriser en fonction des conditions opérationnelles, l'utilisation de ces propriétés aiderait le processus d'aide à l'identification.

En conclusion de cet exposé on pourrait souhaiter que des informations de rayonnement électromagnétiques retrouvent leur place dans ces fichiers comme ne l'exclue d'ailleurs pas la norme mais comme ne le montre pas de manière manifeste la pratique.

Remerciements

THOMSON-CSF remercie le STTE qui a financé l'étude IDAS (Identification Air Sol) au titre de laquelle les travaux présentés ont été en partie développés.

THOMSON-CSF remercie également la CEGN/DGA pour la mise à disposition des données VMAP, ainsi que l'IGN pour la mise à disposition des données BD Topo et BD Carto.

Conception des systèmes de gestion de mission : approches technique et méthodologique

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1. Introduction

Forte de sa compétence dans le domaine de la conduite du vol et plus particulièrement de la gestion du vol notamment sur les programmes majeurs d'avions d'armes Mirage 2000 et Rafale, SEXTANT Avionique s'intéresse depuis plusieurs années au développement de systèmes de gestion de mission permettant une prise en compte temps réel de l'évolution du contexte opérationnel (environnement tactique, météorologique, avion).

Dans le but de définir une fonction embarquée adaptée, des expertises ont été recueillies auprès des opérationnels de l'Armée de l'Air et de l'Aéronavale qui ont permis de déterminer son rôle, son domaine d'emploi, son niveau de performances (en terme de temps de réponse,...), d'interactivité homme-système, et les stratégies de reconfiguration adaptées.

Toutefois, compte tenu de la variété des théâtres d'opération, des missions, des porteurs possibles et de leurs équipements, cette définition ne doit pas être considérée comme unique ou figée. C'est pourquoi les choix d'architecture et de méthodologie de développement effectués doivent favoriser l'adaptabilité de la fonction à l'évolutivité des exigences.

La présente publication décrit ainsi l'approche technique et méthodologique adoptée pour le développement de tels systèmes et se compose de quatre parties. Le chapitre 2 présente la fonction Gestion de Mission telle que définie actuellement. Les chapitres 3 et 4 décrivent respectivement les principes d'architecture retenus et la méthodologie de développement. Le chapitre 5 présente l'environnement de simulation et d'évaluation pilotée de la fonction. Les travaux relatés ici sont soutenus par les services étatiques français (STTE) dans le cadre de marchés d'étude.

2. Définition de la Fonction Gestion de Mission

2.1. Cahier des charges

2.1.1. Caractéristiques des missions considérées

Les recueils d'expertise ont été axés sur les principales missions envisagées actuellement (attaque air/sol, assaut mer et défense aérienne) dans l'optique d'identifier très précisément, en fonction des phases de la mission, les stratégies de reconfiguration habituellement adoptées pour prendre en compte l'évolution moyen/long terme du contexte (tactique, météorologique) ou des paramètres internes avion (temps, pétrole, trajectoire).

Suivant le type de mission considéré, les stratégies peuvent différer : la préservation du potentiel ou l'accomplissement de la mission seront privilégiés. Dans le cadre des missions de plus en plus fréquentes que l'Armée de l'Air et l'Aéronavale sont amenées à effectuer au profit d'opérations de maintien de la paix (Bosnie-Herzégovine par exemple), le coût (humain, financier, politique) de la perte d'un appareil et de son équipage est jugé prohibitif au regard de l'importance de la mission. En cas d'incident, l'objectif de la replanification sera

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alors d'assurer la sauvegarde de l'appareil, en général au prix de l'échec de la mission. Dans d'autres cas, la réussite de la mission sera considérée comme primordiale (hypothèse d'un conflit en Centre Europe), fusse au prix de la perte d'un ou plusieurs avions.

A l'issue des recueils d'expertise, il est apparu une meilleure adéquation entre l'aide apportée par la fonction avec les missions de type attaque Air/Sol et Assaut Mer qu'avec la mission Air/Air.

En effet, étant donné les contraintes extrêmement serrées de l'horaire sur l'objectif des missions d'assaut, le respect du plan de vol (trajet, passage des lignes, phase d'attaque ...) et du timing, déterminés lors de la préparation de mission, sont prioritaires.
En règle générale, la trajectoire en zone amie se fait en altitude et à vitesse moyenne pour minimiser la consommation tandis qu'en zone ennemie, on privilégie le moindre risque en choisissant de voler à très basse altitude le plus vite possible en respectant la situation tactique.
Dans la phase retour, la surveillance du carburant devient plus importante.
Les reconfigurations d'itinéraire en vol, destinées à un avion seul ou au dispositif entier, visent à satisfaire l'ensemble des paramètres de la mission.

Dans le cadre de la mission Air/Air, les besoins en matière de respect du plan de vol, tant du point de vue trajectoire que du point de vue timing sont bien moins importants, la gestion du carburant conservant , elle, toute son acuité.

2.1.2. Contexte opérationnel

Contexte tactique :

La situation tactique est en général bien connue au moment de la préparation de mission, surtout dans les conflits récents où une phase de crise permet l'accumulation de renseignements avant l'ordre d'exécution de la mission.
La connaissance des menaces Air/Air lors de la préparation de mission n'influe pas sur le tracé de l'itinéraire (position et dotation inconnues au moment de la mission) mais elle détermine, pour une part, les caractéristiques du dispositif.
En fonction de la létalité connue de la menace Sol/Air, des capacités des Contre Mesures Electroniques d'autoprotection et de l'importance accordée à la réussite de la mission, l'itinéraire devra contourner impérativement la zone de menace ou accepter de la traverser partiellement en tachant de limiter la vulnérabilité de l'appareil.

Contexte météo :

Les avions modernes étant dotés de capacités IMC (Instrument Meteorological Conditions), l'impact de la météo est globalement assez faible sur l'organisation et le déroulement de la mission. Le pilotage en IMC nécessite pourtant une attention plus soutenue de la part du pilote (phénomènes de désorientation, risque d'abordage).
Dans les conflits de type Bosnie-Herzégovine où la minimisation des dommages collatéraux est une préoccupation constante, les règles d'engagement imposent une identification de la cible. Dans le cas de trop mauvaises conditions (visibilité inférieure à la portée de l'arme), la mission est donc annulée.
Pour l'atterrissage, des conditions météo peu favorables conduisent le pilote à augmenter ses marges de carburant pour être capable d'éventuellement opérer un déroutement.

2.1.3. Hypothèses systèmes armement capteurs

Le besoin opérationnel pour des fonctions de type "Elaboration De Trajectoires", semble fort dans le cadre de missions d'attaque Air/Sol avec pénétration en basse altitude. Le scénario retenu est donc celui d'une attaque d'un objectif unique par tir d'AGL. Destinées à des missions de l'Armée de l'Air comme de l'Aéronavale, la fonction s'adresse à une patrouille de 4 avions dotés de capacité IMC (Instrument Meteorological Condition) et d'un système

MIDS (Multifunction Information Distribution System).

2.2. Définition de la fonction

2.2.1. Principes d'assistance

La fonction "Elaboration De Trajectoires" repose sur une fonctionnalité centrale d'élaboration de trajectoires qui doit permettre des reconfigurations 3D/4D du plan de vol ou de la trajectoire avion compatibles des contraintes globales de la mission (timing, pétrole, trajectographie,...).
Sur cette base, trois types d'assistances sont proposées:
- détection d'événements perturbants,
- propositions de reconfigurations d'itinéraires associées aux détections d'événements
- assistances spécifiques :
  . évaluation d'itinéraires spécifiques (retour, ravitaillement),
  . modifications des contraintes du plan de vol courant,
  . évaluation d'un plan de vol construit par le pilote,
  . changement du Dest,
  . évaluation de l'accessibilité des terrains de recueils
  . fenêtre de consultation

2.2.1.1.Détection d'événements perturbants

Les détections d'événements sont issues des traitements de surveillance du contexte (acquisition d'événements externes, surveillance du respect du timing et des capacités en pétrole, surveillance de la faisabilité de reconfigurations par anticipation telle que rejointe ou régulation en vitesse et plus généralement de la faisabilité de proposition de reconfiguration). Elles ont pour but d'informer le pilote de la dégradation des conditions de réalisation de la mission compte tenu de l'itinéraire en cours. Elles sont filtrées en fonction de leurs importances et de la phase de mission en cours.

Pour mémoire les événements suivants peuvent être émis :
. non respect d'une contrainte temporelle
. non respect de la réserve pétrole sur le terrain
. apparition de menaces nouvelles court ou long terme
. météo défavorable sur zone
. panne conduisant à la remise en cause de la mission

2.2.1.2.Propositions de reconfiguration

Une proposition de reconfiguration est toujours associée à une détection d'événement ou à un écart de trajectoire (spatial ou temporel) effectué par le pilote. Elle représente la solution du système face à l'événement qui est à l'origine du problème. Elle est proposée au pilote à la suite de sa détection et met en oeuvre l'expertise pilote en matière de reconfiguration d'itinéraire.
Les événements donnant lieu à une proposition automatique de reconfiguration sont les suivants :
. non respect d'une contrainte temporelle
. non respect de la réserve pétrole sur le terrain
. apparition de menaces nouvelles court ou long terme.

Ces propositions sont entretenues afin de tenir compte de l'avancement de l'avion. L'entretien s'arrête soit si le pilote valide la proposition qui lui est faite soit si les conditions ne permettent plus au système de proposer une solution (retard excessif par exemple).

Le traitement des autres événements (météo défavorable et panne conduisant à la remise en cause de la mission) est laissé à l'initiative du pilote qui peut alors utiliser les assistances spécifiques.

2.2.1.3.Assistances spécifiques

En fonction du type d'assistance demandée, le renseignement de paramètres peut être nécessaires. Cela implique une interaction avec le pilote qui peut influer sur la dynamique des

traitements à mettre en oeuvre. Les différents cas sont décrits ci-après.

Evaluation d'un itinéraire de retour
Sur demande pilote, le système calcule un itinéraire de retour sur le terrain de recueil le plus proche. Le pilote n'a pas de paramètres à renseigner. L'itinéraire proposé est entretenu tant que le pilote ne l'a pas validé ou n'a pas annulé sa demande.

Evaluation d'un itinéraire de ravitaillement
Le système calcule un itinéraire de rejointe à un pattern de ravitaillement défini en préparation de mission. Aucun paramètre n'est nécessaire. L'itinéraire proposé est entretenu jusqu'à la validation par le pilote ou désactivation de cette assistance au ravitaillement.

Modifications des contraintes du plan de vol courant
Le pilote modifie certaines contraintes du plan de vol (route, timing, réserve de pétrole). Après modification, un nouvel itinéraire est calculé. Les paramètres nécessaires sont les contraintes modifiées et leurs nouvelles valeurs. L'itinéraire 4D obtenu est présenté et considéré automatiquement comme le nouvel itinéraire courant.

Evaluation d'un plan de vol construit par le pilote
Le pilote peut définir manuellement un plan de vol en désignant ou en créant successivement des buts de navigation. A chaque nouvelle désignation d'un but, l'itinéraire rejoignant le dernier but désigné est calculé à partir de la localisation définie par le pilote et présenté. Le processus de construction se termine soit par la validation de l'itinéraire construit soit par son annulation.

Changement du but Dest
Un itinéraire de rejointe est calculé de telle manière que le point de rejointe de l'itinéraire courant se trouve sur le segment précédent le but désigné par le pilote comme étant son prochain but de destination.

Evaluation de l'accessibilité des terrains de recueils
Le traitement d'évaluation de l'accessibilité des terrains de recueils en pétrole est activé sur demande pilote et réactualise en permanence les informations calculées pour tenir compte de l'avancement de l'avion et de sa consommation de pétrole. Le pilote n'a aucun paramètre à entrer. Ce traitement est désactivé par le pilote.

Fenêtre de consultation
Le traitement "fenêtre de consultation" est activé par le pilote lorsqu'il désigne un but. Les informations présentées dans le file de consultation sont réactualisées pour tenir compte de l'avancement de l'avion et de sa consommation de pétrole tant que l'alidade se trouve sur le but. Le pilote n'a aucun paramètre à renseigner.

2.2.2. Traitements de conduite du vol

L'expression du besoin opérationnel se traduisant pour l'essentiel, par l'entretien d'une trajectoire garantissant le suivi de l'itinéraire nominal de la mission et le respect des contraintes associées, la fonction Elaboration de Trajectoires propose un certain nombre de fonctionnalités de génération d'itinéraires. Un ensemble de modules basiques de génération du profil de vol (horizontal, vertical) et d'habillage en temps et en pétrole assure l'élaboration des trajectoires de suivi du plan de vol et servent de support à la mise en oeuvre des trajectoires de reconfiguration.
Ces modules basiques sont :

- générateur de profil horizontal :
cette fonctionnalité a en charge la génération d'une trace sol reliant les buts du plan de vol entre eux compte tenu des contraintes de vol (route imposée, hippodrome, contrainte pour conduite de tir).

- générateur de profil vertical :
cette fonctionnalité génère un profil vertical pour un vol à palier contraint (montées et

descentes comprises), à palier Economique ou bien en mode de suivi de terrain .

- générateur de trajectoires d'évitement de menaces :
les trajectoires générées par cette fonctionnalité prennent en compte la situation tactique afin de proposer un itinéraire contournant les zones menaçantes.

- habillage temps / pétrole :
ce module propose des consignes de vitesse tout le long de l'itinéraire compte tenu des contraintes horaires de la mission et permet une gestion des marges de carburant pour la réalisation de la mission.

3. Une architecture logicielle pour les systèmes de gestion de mission

L'architecture logicielle présentée a été conçue en deux phases possédant des objectifs de complexité croissante. Au cours de la première phase d'étude (phase d'étude de concept), l'architecture devait permettre essentiellement de faire coopérer un ensemble de fonctions de conduite du vol. L'objectif était alors d'étudier ces interactions grâce à une modélisation adaptée de ces fonctions. Au cours de la seconde phase de développement (phase d'optimisation), l'architecture devait permettre de supporter les modes opératoires d'une fonction embarquée et les contraintes temps réel associées. Pour les deux phases l'adaptabilité de la fonction a guidé les choix d'architecture.

3.1. Phase d'étude de concept

3.1.1. Objectifs

Au cours de la phase d'étude de concept, le problème posé était de faire coopérer des fonctions de conduite du vol pour fournir au pilote une aide multi-domaines à la gestion de la mission. Pour chaque type de problème qui peut survenir au cours de la mission, la recherche d'une solution passe par l'intervention de plusieurs de ces fonctions qui sont à la fois concurrentes dans le traitement de certains sous-problèmes et complémentaires pour la résolution complète d'un problème donné. Aucune contrainte n'était imposée quant aux temps de réponse ou quant à une logique opérationnelle de gestion des traitements. A ce stade, le système d'aide est un système de résolution de problèmes dont on cherche à étudier les mécanismes de raisonnement.

3.1.2. Architecture tableau noir

Une architecture multi-agents de type "tableau noir" a été choisie pour sa capacité à intégrer les différents domaines d'expertise impliqués dans la gestion de la mission. Elle comporte trois composants essentiels : un ensemble de **sources de connaissance** (SC) dans des domaines d'expertise propres (appelées aussi modules spécialisés), le module de **contrôle** (ou superviseur) coordonnant le travail des Sources de Connaissance et le **tableau noir** proprement dit constituant l'espace de résolution des problèmes (hypothèses, solutions partielles, solutions complètes).

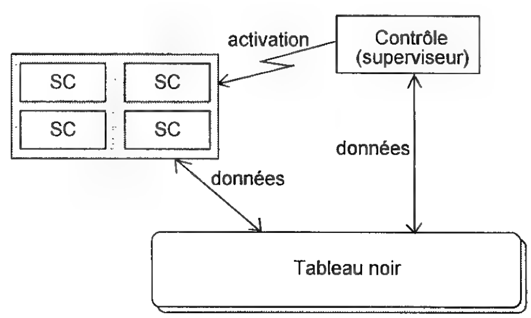

Figure 1 Architecture à base de tableau noir

Le contrôle gère l'activation des sources de connaissance en fonction du problème à résoudre et l'avancement de la résolution. Les sources de connaissance trouvent sur le tableau noir les données du problème et les éléments de solution déjà élaborés par d'autres sources de connaissance et y déposent leur propre contribution.

Le tableau noir contient l'ensemble des objets représentant la mission courante et l'environnement: le plan de vol courant et l'itinéraire 4D courant, l'avion, une base de données de terrains et de buts, les menaces, les données nécessaires au ravitaillement.

Cette architecture permet de séparer clairement les connaissances qui sont propres au domaine (regroupées dans les sources de connaissance) des connaissances de contrôle relatives aux stratégies de résolution (regroupées dans le module de contrôle) qui permettent de déterminer à chaque étape de la résolution du problème les connaissances du domaine à mettre en oeuvre (et donc la ou les sources de connaissances à activer).

Dans cette architecture, chaque fonction de conduite du vol est représentée par un module spécialisé. Le superviseur sélectionne et applique les actions de reconfiguration en fonction du problème à traiter, identifie les différentes combinaisons de coopérations possibles entre modules spécialisés permettant de réaliser ces actions et met en oeuvre la plus adaptée.

Pour cette phase d'étude de concept, le contrôle mis en oeuvre par le superviseur a été volontairement opportuniste. Il est basé sur un cycle en cinq étapes :
- 1) sélection d'actions de reconfiguration pour le problème à traiter,
- 2) mise en oeuvre de ces actions par les modules spécialisés via un mécanisme d'appel d'offre conduisant à l'élaboration d'un itinéraire reconfiguré,
- 3) évaluation de l'efficacité de l'itinéraire obtenu (principalement satisfaction des contraintes portant sur la mission) et du risque qu'il engendre,
- 4) si des contraintes ne sont pas satisfaites ou le risque trop important, la satisfaction de la contrainte prioritaire devient le nouveau problème à traiter,
- 5) Retour à l'étape 1).

Ce fonctionnement permet une modélisation très modulaire des connaissances opérationnelles : chaque élément de connaissance associant un problème à traiter (événement survenu en cours de mission, contrainte non satisfaite) à une ou plusieurs actions de reconfiguration censées résoudre (ou contribuer à résoudre) le problème en question. Une représentation simple et lisible de ces connaissances permet la mise au point des stratégies de résolution. Par ailleurs, le mécanisme d'appel d'offre permet d'ajouter une nouvelle source de connaissance au système de façon totalement transparente pour le contrôle. En effet, celui-ci ne connaît les SC qu'à travers les réponses qu'elles produisent suite à un appel d'offre. En revanche, le fonctionnement opportuniste choisi ne permet pas un contrôle suffisamment sûr de l'enchaînement des actions mises en oeuvre et par voie de conséquence du nombre de cycles de raisonnement.

Cette première architecture a permis d'obtenir des solutions pertinentes pour les différents types d'imprévus envisagés. Par ailleurs, elle a permis de progresser de manière significative dans la structuration des connaissances opérationnelles nécessaires et dans la définition du rôle des modules spécialisés et algorithmes associés. Les enseignements tirés de cette première phase sont développés au paragraphe suivant au regard des objectifs de la seconde phase.

3.2. Phase d'optimisation

3.2.1. Objectifs

De nouveaux objectifs ont été fixés pour cette phase d'optimisation. Il s'agit de permettre le fonctionnement en temps réel d'un ensemble de traitements concurrents activés par l'arrivée d'événements externes ou par le pilote. La définition de ces traitements découle des spécifications de la fonction (voir plus haut). On y retrouve les raisonnements de reconfiguration d'itinéraires étudiés dans la

phase d'étude de concept qu'il s'agit désormais de mettre en oeuvre dans un contexte temps réel conformément à la logique opérationnelle de fonctionnement de la fonction.

3.2.2. Enseignements tirés de la phase précédente

Les principaux enseignements tirés de la phase précédente en matière de choix d'architecture sont les suivants :

1) Les modules spécialisés définis au cours de la phase d'étude de concept correspondaient à des fonctions de conduite du vol. Cela a permis de mettre en évidence des besoins d'interactions entre modules spécialisés : tel module spécialisé a besoin d'utiliser certains traitements élémentaires faisant partie d'un autre module spécialisé. Ce type d'interaction directe entre modules spécialisés dénature l'architecture à base de tableau noir dans laquelle les modules spécialisés ne sont pas censés se connaître mutuellement. Il est donc souhaitable de distinguer les traitements utilisant des connaissances opérationnelles des traitements élémentaires partageables et de rendre ces derniers indépendants des modules spécialisés.

2) La mise en coopération des modules spécialisés se faisant par réponse à appel d'offre, l'introduction d'un nouveau module spécialisé ne modifie pas le contrôle garantissant une forte évolutivité. Toutefois, on constate que les réponses aux appels d'offre du superviseur conduisent très souvent aux mêmes schémas de coopération entre modules spécialisés. Ces quelques schémas sont en fait toujours les mêmes séquences de traitements élémentaires hébergés par certains modules spécialisés. Compte tenu de la remarque 1), ce type de coopération pourrait avantageusement être déplacé vers les modules spécialisés qui assurerait ainsi un contrôle local sur les traitements élémentaires.

3) Enfin, les objectifs de cette seconde phase en matière de maîtrise des temps de réponse, ne permettent pas de conserver simplement un contrôle opportuniste.

3.2.3. Architecture de la fonction Gestion de Mission

La conception de l'architecture s'appuie sur une analyse globale des traitements (analyse

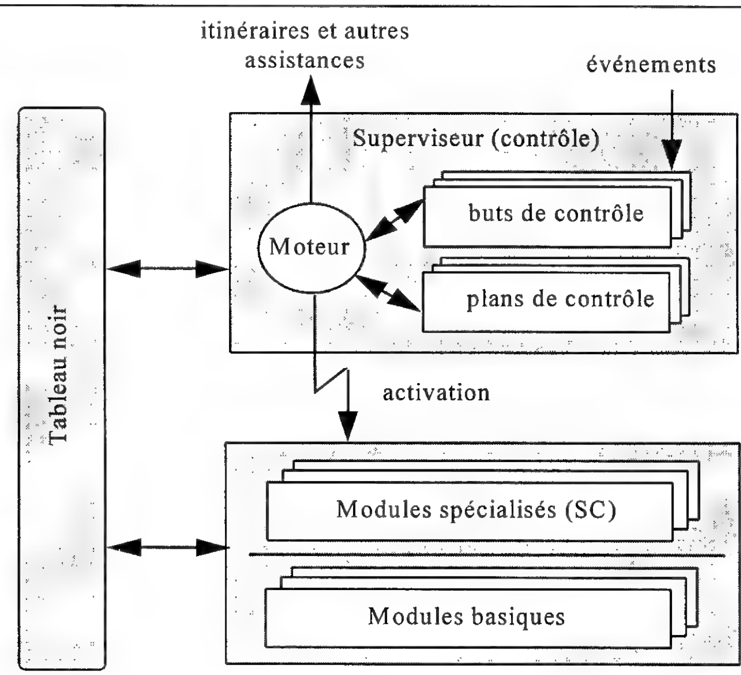

Figure 2 Architecture de la fonction Gestion de Mission

statique (entrées/sorties, dépendances de données) et analyse dynamique (périodicité, condition d'activation et de terminaison, priorités, qualité requise)) et profite des enseignements tirés de la phase précédente.

L'architecture à base de tableau noir est reconduite mais avec une structuration différente des modules spécialisés et un contrôle favorisant la maîtrise des temps de réponse et pouvant supporter la logique opératoire de la fonction (figure 2).

Evolutions des modules spécialisés

Les modules spécialisés ont subi deux évolutions :
1) les traitements élémentaires utiles à plusieurs modules spécialisés ont été regroupés pour former une base d'algorithmes accessibles à tous,
2) les modules spécialisés assurent seuls l'élaboration d'un itinéraire 4D complet correspondant à un type de reconfiguration donné en gérant les appels aux traitements élémentaires nécessaires.
Chaque module spécialisé est ainsi responsable d'un type de modification de l'itinéraire directement issu des recueils d'expertise et aisément identifiable dans cette expertise.

Evolutions du contrôle

De nombreuses architectures ont été proposées afin de doter des systèmes de replanification de capacités temps réel.

Dans ces architectures de replanification réactive, deux types de plans sont souvent manipulés. Le premier type est celui objet de la replanification. Dans notre cas, les plans de ce premier type sont les plans de vol et les itinéraires objets des reconfigurations.
Le second type de plans décrit l'activité interne du système de replanification. Les actions du second type sont des actions de modification de plans du premier type. La replanification s'appuie ainsi elle-même sur l'exécution de plans. On parle alors de plans de contrôle pour désigner ces plans du second type.

Dans un contexte temps réel les plans de contrôle s'avèrent être un outil efficace de gestion de l'activité du système. Les techniques de contrôle des systèmes de replanification rejoignent ici les techniques de contrôle des systèmes de multi-agents de type tableau noir. Les plans de contrôle présentent l'avantage d'être des structures de données aisément modifiables et lisibles et permettent de maîtriser le nombre d'étapes de raisonnement effectuées (un plan à un longueur ou une profondeur finie et connue).

La tâche principale du contrôle consiste alors à déterminer à tout instant les plans de contrôle à mettre en oeuvre compte tenu des événements à traiter, de leurs échéances et importances respectives.

Les plans de contrôle sont analogues à des sources de connaissances dont le rôle n'est pas d'élaborer des informations d'aide au pilote mais de définir la stratégie pour élaborer au mieux ces informations. Le superviseur traite ainsi les plans de contrôle comme des sources de connaissance activables au même titre que les autres.

Les événements en entrée du superviseur sont transformés en buts à atteindre associés à une priorité de traitement. Le superviseur recherche ensuite le meilleur plan de contrôle sachant traiter le but. La mise en oeuvre de ce plan conduit à l'activation de SC ou d'autres plans de contrôle.
Cette architecture a été implémentée et est actuellement en cours de test. Sa modularité devrait favoriser l'adaptabilité de la fonction aux modifications d'expertise, de type de mission ou de théâtre d'opération (principalement à travers la définition des buts, plans de contrôle des SC et des objets présent sur le TN). Cette capacité à s'adapter s'appuie aussi sur la méthodologie et les outils de développement.

4. Méthodologie de développement

Ce paragraphe aborde différents aspects de la méthodologie de développement de système de gestion de mission et propose une approche pratique issue de l'expérience de tels développements. Cette approche vise en particulier à améliorer la réactivité de prise en compte des besoins et de l'expertise des pilotes. On s'intéresse ici aux problèmes liés aux spécificités fonctionnelles et techniques de ces systèmes sans prendre en compte à ce stade les contraintes de l'embarcabilité sur la méthodologie de développement.

4.1. Adaptation du cycle de développement

La pratique du développement de prototypes de systèmes de gestion a permis de clarifier les étapes de développement nécessaires, les relations entre ces étapes et le rôle des différents modèles utilisés. Cela conduit aux étapes de développement représentées Figure 3.

Il s'agit en fait d'une adaptation du processus de développement en V. On se démarque donc ici des processus de développement centrés sur l'acquisition et l'implémentation itérative de connaissances avec une représentation des connaissances souvent déterminée a priori (règles par exemple).

Au contraire, on cherche ici à privilégier la définition du système au choix d'une représentation des connaissances ou d'une technique d'implémentation, les connaissances recueillies contribuant aux étapes "classiques" de développement.

Ce schéma permet en particulier d'expliciter les rôles respectifs des tâches de recueil et formalisation d'expertise vis-à-vis des tâches de spécification et d'implémentation.

L'information issue des recueils d'expertise est utilisée en premier lieu pour l'analyse des besoins de l'utilisateur et oriente ainsi la spécification du système. Celle-ci s'appuie par ailleurs sur une connaissance des principes d'assistance étudiés ou préconisés dans le domaine de l'assistance au pilotage (répartition

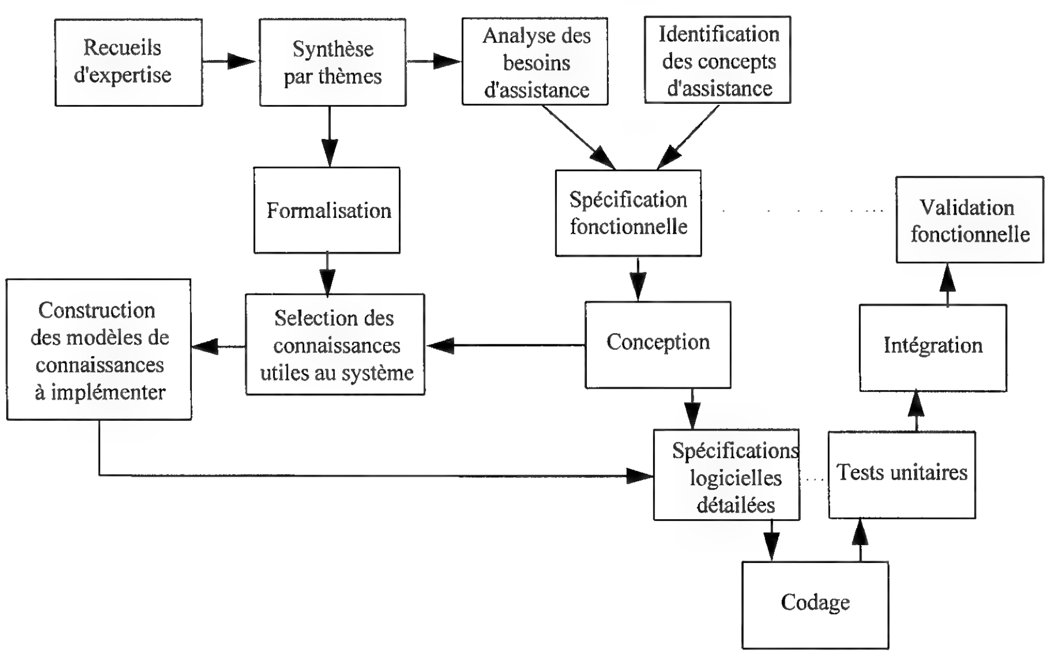

Figure 3 Etapes de développement

statique ou dynamique des tâches, aide à l'anticipation, détection d'erreurs, reconnaissance d'intentions).

Partant de cette spécification, le développement du système pourrait se poursuivre de façon conventionnelle. Le choix se fait au moment de la conception qui détermine les solutions techniques permettant de réaliser la spécification. Concrètement la conception aboutit à la définition d'une architecture logicielle et de modules logiciels. Selon les problèmes fonctionnels à résoudre on peut faire appel soit à des modules logiciels conventionnels soit à des modules à base de connaissance mettant en oeuvre les techniques de raisonnement adaptées (déduction, raisonnement à base de cas, résolution de contraintes, parcours d'arbres de décision, etc) et les représentations associées.

Si la conception fait apparaître de tels modules à base de connaissance alors les connaissances recueillies trouvent une seconde utilisation en alimentant ces modules. La définition de leur rôle permet d'isoler les connaissances utiles et on considère qu'un changement de représentation est nécessaire à ce stade afin de respecter les choix de conception en matière de représentation des connaissances. L'étape de codage comporte alors une part (de taille variable selon les systèmes) consacrée à l'implémentation des connaissances exploitées par ces modules.

Cela conduit par ailleurs à distinguer un modèle d'expertise pilote indépendant de tout système (et dont le formalisme n'est pas lié à telle ou telle technique d'implémentation) et un ou plusieurs modèles dépendant de la conception et destinés à l'implémentation.

4.2. Traitement des recueils d'expertise

Les recueils d'expertise et leur analyse sont souvent considérés comme des tâches coûteuses. Deux types de difficultés sont évoquées ici et des solutions proposées.

Une première source de difficulté provient de la taille considérable des corpus constitués rendant leur utilisation quotidienne fastidieuse. On cherche donc légitimement à utiliser un formalisme pour synthétiser les connaissances recueillies tout en garantissant cohérence et complétude. Or, cette formalisation peut se révéler difficile à utiliser car très dense et parfois impénétrable pour un lecteur externe. Ainsi, une autre forme plus lisible et facilitant la communication a été définie. Il s'agit de ce que nous appelons une synthèse par thèmes regroupant l'ensemble des éléments de connaissances (description d'un objet, d'un problème, d'une stratégie de résolution) présents dans un corpus. Chaque élément est référencé par rapport au corpus et peut appartenir à plusieurs thèmes évitant ainsi toute classification rigide.
La formalisation est ensuite effectuée à partir des synthèses par thèmes. Cela permet un gain de temps appréciable car les redondances et contradictions apparentes du corpus et l'éparpillement des informations traitant d'un même thème ont été traités par la constitution de ces synthèses.

Une seconde source de difficulté pour le cogniticien provient de la difficulté à converger vers une compréhension cohérente des propos de l'expert créant le besoin d'itérer sur certains sujets. On constate ainsi fréquemment des problèmes d'interprétation dus à un manque de précision concernant les hypothèses sous-jacentes aux questions posées. Ces hypothèses implicites ont toutes les chances d'être différentes entre le cogniticien et l'expert.
Cela nous a conduit à définir un protocole d'entretien imposant une définition très précise du contexte de l'entretien. Ce contexte comprend un ensemble de 36 paramètres explicités avec l'expert en début d'entretien. Parmi ces paramètres : le type d'avion considéré, ses principaux équipements, son armement, le type de dispositif, le contexte tactique et opérationnel, une mission type à effectuer.

Les réponses obtenues ne sont considérées valides que dans ce contexte et un travail de généralisation est ensuite nécessaire afin d'analyser l'influence d'un paramètre du contexte sur les réponses obtenues.
Cet effort de précision a permis de clarifier ce qui apparaissait à tort comme des incohérences du discours de l'expert ou des incohérences entre plusieurs experts interrogés sur le même sujet.
Le développement d'un support informatique plus puissant (gestion documentaire hypertexte avec fonctions dédiées) doit permettre de développer cette approche.

5. Evaluation

5.1. Méthodologie d'évaluation

La simulation de la fonction Gestion de Mission actuellement en cours de développement, doit être évaluée par les pilotes des Etats Majors de l'Armée de l'Air et de la Marine Nationale qui ont contribué aux recueils d'expertise.
Cette évaluation a lieu sur les moyens du banc de simulation de concepts de conduite du vol de SEXTANT Avionique sur la base de scenarii de missions Air/Sol définis avec les Opérationnels au cours des recueils d'expertise.
Le système implanté sur le banc de simulation permet au pilote d'observer les trajectoires solutions proposées pour remédier à l'apparition d'imprévus apparus à tout moment dans le déroulement de la mission, tout en continuant de piloter l'avion. Le pilote voit son avion évoluer sur l'image graphique du théâtre des opérations apparaissant sur l'écran placé dans le cockpit devant lui. Il peut sélectionner la trajectoire qu'il souhaite suivre et embrayer son pilote automatique afin d'être guidé sur celle-ci.

5.2. Environnement d'évaluation

SEXTANT Avionique dispose d'un banc de simulation pour applications militaires capable d'accueillir de nouveaux concepts de pilotage sous forme de fonctions logicielles.
Ce banc comporte la simulation d'un environnement avion "grands mouvements" avec ses moteurs, ses capteurs principaux et ses moyens de radio-navigation.

5.2.1. Architecture matérielle

L'architecture matérielle se compose :
- d'un "cockpit" de pilotage doté de moyens simulés de pilotage de base (manche, manette) et de visualisations multifonctions tête haute, moyenne, et latérales,
- d'une simulation de paysage 3D,
- de calculateurs temps réel connectés entre eux par une liaison haut débit,
- d'un ensemble de stations de travail supportant la fonction Gestion de Mission et communiquant selon la norme CORBA.

5.2.3. Architecture fonctionnelle

La simulation est composée de quatre blocs fonctionnels :

- **bloc Base De Données** constitué par:
  - un fichier TERRAIN complet "altimétrie et planimétrie"
  - une base de données Plans De Vol
  - une base de données BUTS
  - une base de données SITAC (tactique)
  - une base de données METEO

- **bloc Avion et Système** constitué par
  - l'environnement Avion Moteur Capteurs
  - la fonction de pilote automatique
  - la gestion du cockpit de pilotage
  - la conduite de la simulation

- **bloc IHM** :
  - visualisations tête moyenne, tête latérales développées en environnement graphique X11,

- **bloc Noyau Fonctionnel** qui comprend:
  - un superviseur
  - des modules spécialisés

La figure 4 représente l'architecture matérielle et logicielle et schématise les flots de données.

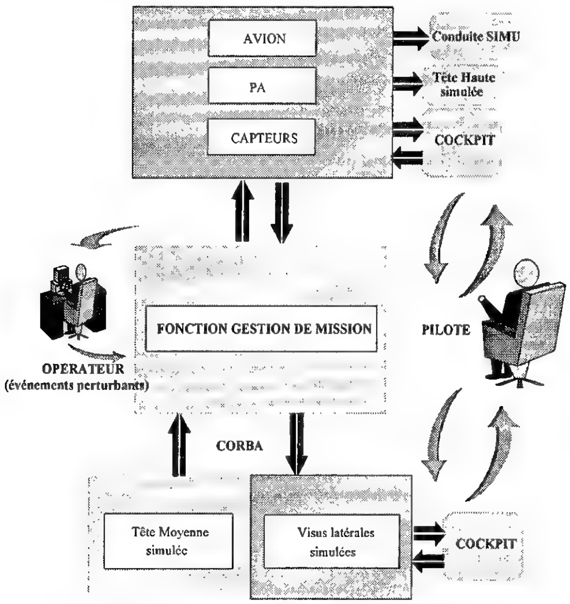

figure 4 Architecture de la simulation

6. Conclusion

La présente publication décrit les travaux récents réalisés par SEXTANT Avionique dans le domaine de la Gestion de Mission. Une fonction d'assistance à la gestion de la mission est présentée en terme de fonctionnalités d'assistance, d'architecture et de méthodologie de développement. La recherche de gain d'adaptabilité grâce aux choix d'architecture et de méthodologie est mis en évidence. Les travaux à venir à court terme concerne l'évaluation en simulation pilotée de la fonction. Par ailleurs, les axes de développement incluent également :

- l'extension du domaine d'emploi de la fonction (autres théâtres opérationnels, autres types de missions),
- le renforcement des moyens ou techniques favorisant cette extension par la définition et la mise en place d'outils informatiques complémentaires en support du cycle de développement présenté,
- l'embarcabilité de la fonction sous les aspects technologique, méthodologique et réglementaires.

MISSION PLANNING SYSTEMS: CUBIC MULTIPLIERS

by
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1 Introduction

AGARD Advisory Report No. 296, published May 1991, contains the definition of a planning system for aircraft missions: "A system that allows all the available and pertinent information to be used to plan a mission to achieve certain objectives in an optimum and near-optimum way, and also data that describes the mission to be loaded into the aircraft. With respect to objectives, operating and technology mission planning systems can be considered as multipliers." This paper discusses some topics related to these multipliers.

The National Aerospace Laboratory NLR, in The Netherlands, has a long time experience in development and production of military aircraft mission planning systems (figures 1 and 2). In 1975 already NLR studied the feasibility of "rear-port tube" graphic display systems for mission planning purposes. This type of display system provided the capability to project map information via a rear-port on the innerside of the display screen, so the screen itself could be applied to compose and show an overlay on the projected map. However, inadequate positioning accuracy of the overlay on the map with respect to navigation requirements made this rear-port tube graphics technology unfeasible for military aircraft mission planning systems. NLR's assessment of technology improvements is part of the section on technology (section 4).

The most prominent multiplier is directly related to the mission objectives. Awareness of the actual battle theatre and several types of advices (weapon - to - mission objectives suitability, minimum risk route, attack manoeuvring etc.) are improving principally and practically the chances on mission success. Section 2 of this paper highlights two ingredients of this multiplier:

- in the framework of interoperability the standardization of data exchange;
- in the framework of user friendliness a user definable electronic continuous map area.

The second multiplier is the capability of mission planning systems to play a role in the training of military pilots with respect to the execution of real missions. To make this multiplier effective three conditions have to be fulfilled:

- the mission planning system supports all mission types due to be exercised;
- a metric system is available to assess the planned and sometimes also executed missions in detail;
- fake realistic battle theatres are composed in such a way that progress in training can be determined.

This second multiplier will be discussed in section 3.

Mission planning systems are driving the technology: the third multiplier. Routing systems need always geographic/topographical/reconnaissance information and this information mass is e.g. driving storage capabilities, data compression techniques, and remote sensing derivatives. This subject will be discussed in section 4.

2. The first multiplier: improved mission execution

An electronic information system exists of three components: hardware, software and information. These three components are all essential: the quality of information defines for the mayor part the value of the multiplier. A large part of this information is either unchanging or very slowly changing, so that update of this is rarely necessary and in no way critical. However some of the information - e.g. the geographical position of both friendly and enemy assets - could be changed frequently to correspond to rapidly changing real world situations.

2.1 NATO standards for data exchange

The mobility of military forces - needed because of an essential task of NATO: embanking of local conflicts - and the improved mobility of enemy threats hamper obtaining correct and up-to-date information. Of course it is an option to prepare a mission without using this information: in that case a judicious risk analysis is recommended. The NATO approach to facilitate the transfer of information is to define "exchange standards": standard information formats.

What NATO data exchange standards are available to load this pertinent information (see table 1) into the mission planning data base? This investigation is limited to the information sets in the scenario cluster, because of the rapidly changing character of most of these information sets. The first column of table 2 contains the name of the information subset involved, the second column the number and the edition of the NATO Standard Agreement (STANAG), the third column the designation and covering of the related standard.

Table 2 shows that only for geographical information data exchange STANAGs have been defined. The important intelligence data STANAG is a concept version; for meteo only a communication STANAG is available. For navigation data a STANAG for obstacles is available. In the framework of data exchange standards for command and control still a lot of work has to be done.

Paper presented at the AGARD MSP Symposium on "Advanced Architectures for Aerospace Mission Systems", held in Istanbul, Turkey, 14-17 October 1996, and published in CP-581.

Table 1 MSS/P DATABASE

information	breakdown	remarks
Scenario cluster		
Geographical info.		
Digital Landmass SYSTEM	terrain elevation and feature data	
1:50/100/250,000 electr. maps	continuous areas	UTM projection
1:500,000 electronic maps	continuous areas (TPC, LFC)	Lambert projection
1:2,000,000 electronic maps	map sheets	Lambert projection
Schematic maps (WVS)		DMA product
Intelligence Info.		
Threats*	AOB, EOB, GOB, MOB, Events, Latent threat	point co-ordinates
Planning lines*	including FLOT, FSCL, EFSCL, RIPL	split up in line parts
Nuclear incidents*		for presentation only
Meteorological info.		
Airfield weather*	actual and forecast	
Significant weather chart*	lines, symbols and text	
Aircraft performance weather*	grid position, wind speed/direction, temperature, QNH	mainly for Ferry a/c performance calc.
Navigation info.		
Airspace management*	routes, zones, lines, boundaries, traverse levels	validity periods
Low flying restrictions	lines, areas, circles	validity periods
Obstacles	Elevations in AGL and MSL	limited availability for low level flights
Friendly airfields	status of ATC, runway, weather, X-serv.	necessary for diversion
Airfield ICAO codes	position and capabilities	
Standard waypoints		to support fast planning
Flight information regions	region identifiers + latitudes/longitudes	for air traffic control in peace time
Magnetic corrections		predicted for 5 years
Aircraft and weapon cluster		
Aircraft performance		implemented as software library
Aircraft configuration	tailnumber specific and generic	
Weapon Stores config.	aircraft/station/stores standard, pilot selectable	standard configurations can be predefined
Tactics cluster		
Tactical scenario	altitude bands, risk levels, EW conditions, threat type	threat presentation and risk calculation
Weapon effectiveness	predefined by NATO, local adaptations possible	
Manoeuvres	run-in, attack, delivery	fuse arming/safe escape/ fragmentation
Route (Preplanned)	air-to-ground missions, air defence sectors, CAP-pos.	
Communications	including IFF/SIF codes	
Default and control parameters		
Defaults		to speed up standard planning sessions
Control parameters	ID. of info. source, map scale/type and symbols	user friendliness

* also obtainable from other CCIS systems

Table 2 NATO DATA EXCHANGE STANDARDS

Information subset	STANAG	Remarks
Geographical		
- terrain elevation	3809 (ed. 3, 1995)	MIL-D-89020
- feature analysis	-	MIL-D-89006
- electronic maps NATO	4387 (concept)	ASRP
DOD	-	MIL-A-89009 ADRG
- digital maps	7074 (ed. 1, 1995)	DIGEST
Intelligence	2433 (concept)	AIntP3
Meteo	6014 (ed. 2, 1995)	AWP3(A), only communications
Navigation		
- airspace management	-	ATP 40 (A), 1989
- low flying restriction	-	CALF, AFCENT
- obstacles	2123 (ed. 3, 1988)	obstacle folder
- friendly airfield	-	ICAO
- airfield ICAO codes	-	ICAO
- standard waypoints	-	-
- flight info regions	-	ICAO Doc. 8400/3
- magnetic corrections	-	British Geological Survey

2.2 NATO standards for geographical data exchanges and userfriendliness

The geographical STANAGs mentioned in table 2 are used mainly for data exchange. What effort has to be spent to make this exchange data ready for use? The three geographical subsets under consideration will be discussed separately.

2.2.1 Digital Terrain Elevation Data (DTED)

Each terrain elevation is compressed into two 36-bits words, the file size is a 1-degree by 1-degree geographical cell. The conversion effort is defined by the collection of the required cells and the decompression into usable items. It is recommendable to spend this effort once prior to the use of the information in the application.

2.2.2 Electronic maps

Table 2 shows two exchange standards for electronic (raster) maps. The first one is the DMA exchange standard, adopted by the USA DOD specifications under MIL-A-89007. NATO has not copied this standard completely but defined STANAG 4387. A significant difference between both standards is the defined raster resolution (MIL-A-9007: 250 pixels/inch, STANAG 4387: more flexible, nominal 250 pixels/inch, variations allowed).

Both standards for arc raster products data exchange are dealing with the conversion of paper map sheets into electronic map sheets in a non-equidistant projection system. If the user requirements for the mission planning system are satisfied by separate non-equidistant electronic map sheets, there is no effort needed any more. In case the user requirements for the mission planning system are requesting scrolling over a continuous area (a number of electronic map sheets defined by the operational user), a considerable effort is necessary.

The above mentioned scrolling requirement is most of time due to combined tactical objectives: overview of (attack) scenario and a high level of detail for mission success. Especially if 1:50,000; or 1:100,000 scale maps are needed for the level of detail; map sheets have to be glued together for overview purposes.

The effort to glue maps together is considerable due to:

- the required navigation accuracy in attack manoeuvring;
- variations in map sheet sizes and in colour definitions caused by the traditions of the national geographical/topographical services;
- deviations (e.g bulges exceeding the defined map sheet size) and defects of paper map sheets (e.g smaller than the specified area, or folded).

The NLR Electronic Map Area Production System (EMAPS) copes with these problems (figure 3).

2.2.3 Digital Maps

STANAG 7074 provides the rules for the transfer formats of geographical information existing of coordinates and attributes for each map item. Already a long time the user community is waiting for this digital map information with a high expectation level. It cannot be avoided that these users will be disappointed.

This disappointment is caused mainly by the lack of real user requirements. The national topographical/ geographical services contributed to the STANAG in such a way, that the digital geographical information may be used to reconstruct the original map sheet. The topographical/geographical services will have the full profit of the much better update possibility.

If the user needs with respect to geographical information are satisfied by separate sheets, there is no effort needed any more, just the same as for electronic maps. The advantage for the user will be that the map producer is able to provide updates faster and at lower cost. If the user needs are requesting continuous map areas, the effort to realize these areas can not yet be estimated due to the lack of experience. It is not impossible that electronic maps will be used for a longer period than previously expected.

3. The second multiplier: uniform training in mission execution

After the pilot obtained his flying certificate, he needs an additional training in order to become a competent mission executor. The employment of a mission planning system in this training for mission execution has several advantages:

- uniformity in training is improved;
- uniformity in presentation of battle theatre is assured;
- exercises can be repeated easily, also after completion of the training.

In the introduction of this paper three conditions have been mentioned. The mission planning system needs to support all mission types that have to be trained and exercised; this includes of course the airforce specific tactics in mission execution. The way to consider the other two conditions (metrics and fake scenario) is to take them together. Fake realistic scenarios have to be built in increasing difficulty level and a appreciation figure is attached in case the mission execution problem has been solved properly.

4. The third multiplier: technology driver

The second paragraph of the introduction tells the story of the rear-port tube graphic systems, being at that time the only possibility to present multicolor maps to the user. Disapproval - due to the required navigation accuracy - postponed the presentation of multicolor maps for mission planning for several years. Table 3 shows the evolution of the peripherals/workstations for the mission planning systems developed by NLR.

Table 3: EVOLUTION OF MISSION PLANNING WORKSTATIONS

MOT&E System (1979 - 1981)	Phase 1 + Pilot System (1981 - 1995)	S.O. CAMPAL System (1985 - 1988)	MSS/CAMPAL (1991 - 1994)	MSS/PANDORA (1996 -)
• a-N display	• a-N display	• a-N display		
• printer	• printer	• graphics printer		
	• colour graphics display	• 2D colour image display (1024x1024 pixels)	• 3D colour graphics display (1280x1024 pixels)	• 3D colour graphics display (1 2 8 0 x 1 0 2 4 pixels)
	• digitizer (1x1.4 m)	• digitizer (1x1.4 m)		
		• colour hard copy unit (A3)	• colour hard copy unit (A3)	• colour hard copy unit (A4/A3)

Also the technology progress of foreground/background memory and computer speed played a significant role. Some examples:

- MSS/Campal has a 1 Gigabyte harddisk and a 1 Gigabyte optical disk; MSS/Pandora has a 8 Gigabyte harddisk and no optical disk any more; response time for geographical information have been decreased from some minutes to some seconds;
- the current computing speed enables scrolling of geographical information at a speed of 8Hz.

"Computer based mission planning is a technology driver" is the statement. For the time being this statement remains valid. Mission planners want to have a overview over the entire (mission) area of interest. To the opinion of some operational users scrolling is only a poor replacement for this overview. The requested screen size is about 1 meter by 1 meter. More computer speed is needed because of 3D terrain presentations and verification of terrain coverage during low flying (fixed wing and rotorwing aircraft).

5. Concluding remarks

The cubic multiplier statement is discussed only for ground based mission planning systems. In the case the mission planning task is split over a ground based component and an aircraft component the statement is not changing essentially.

The significance of mission planning systems is demonstrated at the most, if the tasked mission is complicated and has to be executed in a complex and relatively unknown area. To experience the multiplier in extreme circumstances, training in more simple circumstances is highly recommended.

6. Acronyms

ADRG	Arc Digital Raster Graphics
AFCENT	Allied Air Forces Central Europe
AGARD	Advisory Group for Aerospace Research and Development
AGL	Above Ground Level
AIntP	Allied Intelligence Publications
AOB	Air Order of Battle
ASRP	Arc Standard Raster Product
ATC	Air Traffic Control
ATP	Allied Tactical Publication
AWP	Allied Weather Publication
CALF	Chart Amendment Low Flying
CAMPAL	Computer Aided Mission Preparation at Airbase level
CAP	Combat Air Patrol
CCIS	Command and Control Info. System
DIGEST	Digital Geographical Standard
DMA	Defense Mapping Agency
DOD	Department of Defense
DTED	Digital Terrain Elevation Data
EFSCL	Emergency Fire Support Coordination Line
EMAPS	Electronic Map Area Production System
EOB	Electronic Order of Battle
EW	Electronic Warfare
FLOT	Forward Line Own Troops
FSCL	Fire Support Coordination Line
GOB	Ground Order of Battle
ICAO	International Civil Aviation Organization
IFF	Identification Friend of Foe
LFC	Low Flying Chart
MOB	Missile Order of Battle
MSL	Mean Sea Level
MSS	Mission Support System
MSS/C	MSS/CAMPAL
MSS/P	MSS/PANDORA
NATO	North Atlantic Treaty Organization
NLR	National Aerospace Laboratory NLR
PANDORA	Planning of Aircraft Navigation for Defensive, Offensive and Reconnaissance Airtasks
QNH	Airpressure (milibar) above MSL
RIPL	Reconnaisance and Interdiction Planning Line
SIF	Selective Identification Feature
S.O. CAMPAL	Semi-operational CAMPAL
STANAG	Standard NATO Agreement
TPC	Tactical Pilotage Chart
UTM	Universal Transverse Mercator
WVS	World Vector Shore Line

Fig. 1 - MSS/C at Volkel Airbase (courtesy Volkel)

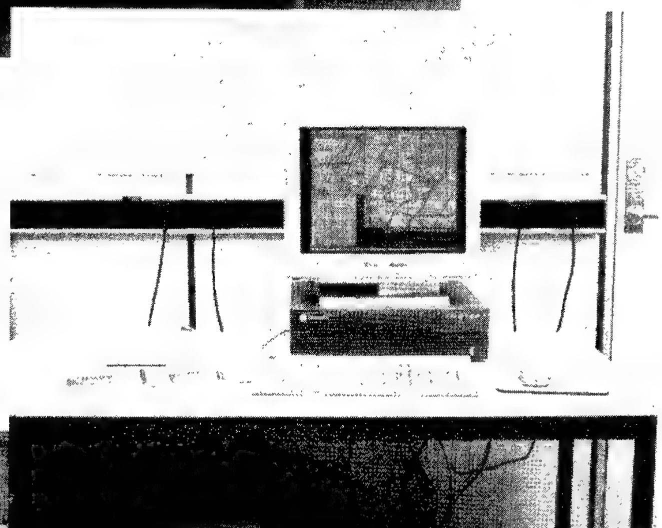

Fig. 2 - Pandora mission support system

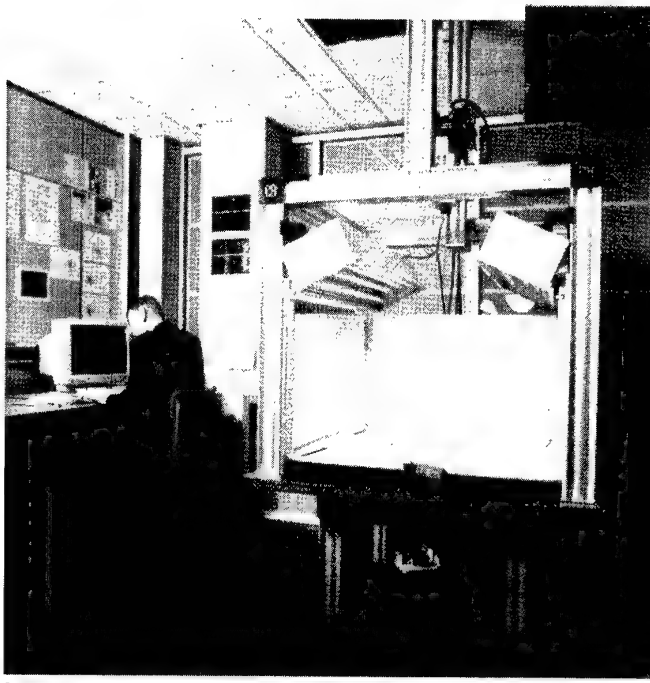

Fig. 3 - NLR Electronic Map Area Production System

C724-01a

Système d'enregistrement et restitution de mission

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SUMMARY

SAGEM S.A. company presents an architecture for embedded recording of multiple video signals and digital data on an single tape, and their ground restitution.

The System Emports Interface Box (BISE) is an hardened equipment, mounted on ACE/Rafale aircraft. It manages all interfaces between aircraft and stores, following the MIL-STD-1760 standard: digital buses, video signals and synchronisation/blanking signals. One of its function is to realize the time multiplexing and data marking of several video signals, for mission recording on magnetic tape.

A ground PC-based equipment has been developped in parallel for the restitution of these video signals and data. Some data are used to synchronize the visualization of the video source choosen by the operator.

The considered evolutions of this architecture are discussed, with digital video recording and restitution.

A new concept is also proposed, for immediate on-board video restitution.

1. PRESENTATION

Le système embarqué de conduite de mission permet au pilote d'exploiter les données qui ont été préparées pour les différentes phases de sa mission. Il assure également l'enregistrement de mission.

La conduite d'une mission est aujourd'hui facilitée par la préparation qui en est faite au sol. Les différentes actions et leur séquencement peuvent être préparés et optimisés pour un ensemble d'appareils. Après la mission, sa restitution avec exploitation des données en rejeu est nécessaire aux opérationnels pour évaluer le niveau d'obtention des objectifs.

Outre ce premier niveau d'exploitation, la restitution de la mission doit également servir à un deuxième niveau pour évaluer la manière dont la mission a été remplie. Ce retour d'expérience doit servir à optimiser les procédures de préparation.

Le choix des données à enregistrer pendant la mission poursuit donc ce double objectif. Le nombre des informations à enregistrer est en constante augmentation, avec des signaux vidéo pour une grande part.

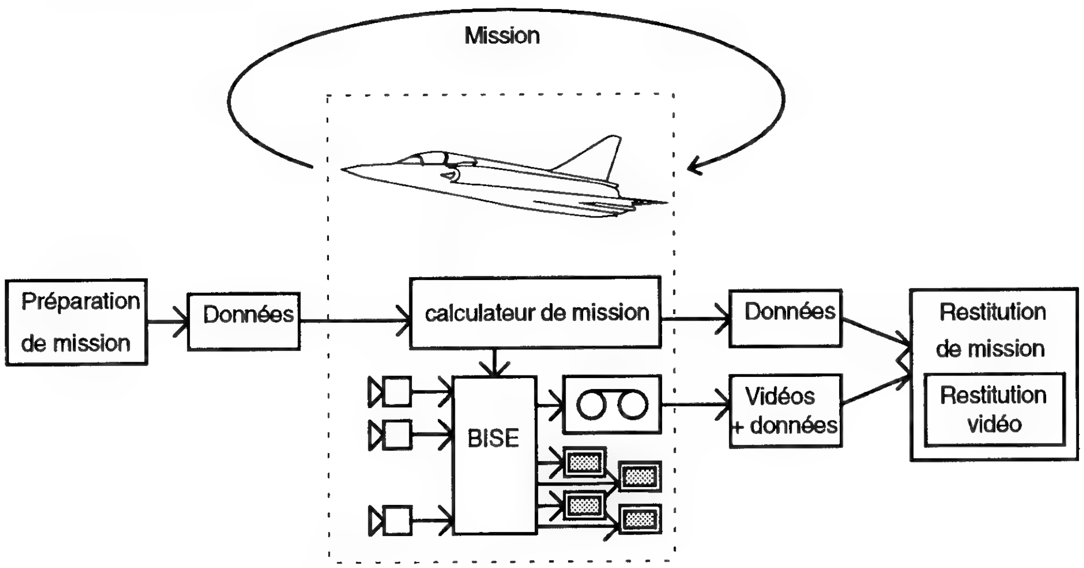
Nous présentons le matériel embarqué d'enregistrement de mission qui a été développé spécifiquement pour l'ACE/RAFALE, ainsi que le système de restitution sol. Nous tracerons les perpectives d'évolution d'un tel ensemble.

Nous décrirons également un équipement permettant lorsque nécessaire une exploitation de données vidéo immédiate par le pilote, pour décision locale sur le déroulement de la mission.

Paper presented at the AGARD MSP Symposium on "Advanced Architectures for Aerospace Mission Systems", held in Istanbul, Turkey, 14-17 October 1996, and published in CP-581.

2. CONTEXTE

2.1. CHAINE FONCTIONNELLE



L'intérêt de la préparation de mission est de définir et rassembler les données de toute nature qui seront utiles au pilote, ou qui permettront au système de conduite de mission de se configurer différemment au fur et à mesure des différentes phases programmées. Les données dépendent des capacités des Systèmes de Navigation et d'Attaque (SNA) des avions, qui deviennent de plus en plus complexes et nécessitent des volumes sans cesse croissants. Elles sont préparées pour chaque appareil sur un support de données extractible, comme des mémoires silicium ou disques durs durcis.

Pour permettre la restitution de mission et l'analyse opérationnelle, des informations sont enregistrées à bord. Ce sont essentiellement des signaux vidéo et audio, des données numériques avion et des évènements. Ces informations sont stockées sur des supports extractibles, qui peuvent être ceux utilisés pour les données d'initialisation.

L'enregistrement du signal de plusieurs sources vidéo (capteurs, écrans pilote, poste de pilotage...) nécessitait jusqu'à maintenant la mise en place à bord d'autant de magnétoscopes que de signaux à enregistrer. SAGEM S.A. a développé une fonction de multiplexage temporel, permettant d'enregistrer plusieurs signaux vidéo sur un seul magnétoscope. Cette nouvelle fonction est implantée dans un équipement qui a été développé pour l'avion ACE/Rafale, qui gére l'interface du système de navigation et d'attaque avec les emports.

2.2. BOITIER BISE

Le Boîtier d'Interface Système - Emports (BISE) est un équipement durci, embarqué sur l'avion d'armes ACE/Rafale de Dassault Aviation. Il est aujourd'hui prêt à être produit en série. Il gère toutes les interfaces entre le Système de Navigation et d'Attaque de l'avion et les Emports, suivant la norme MIL STD 1760, qui spécifie les interfaces des points d'ancrage des emports sur l'avion, pour assurer de plus en plus la compatibilité des emports avec plusieurs avions.

Cet interface remplit les fonctions de:

- gestion de données. Une passerelle informatique assure le couplage entre le bus numérique principal de l'avion 3910 et les bus 1553 desservant les emports,
- gestion de signaux de synchronisation /blanking, avec commutation de 12 voies vers 28,
- gestion de signaux vidéo au standard Stanag 3350, avec plusieurs fonctions.

Les fonctionnalités vidéo BISE comportent:

- la synchronisation de tous les signaux vidéo de l'avion. Un signal de synchronisation généré en interne est envoyé à tous les équipements vidéo comportant une entrée de synchronisation externe. Le Boîtier assure la synchronisation de signaux provenant de sources non synchronisables.

- la commutation de signaux vidéo large bande 20 MHz. Une matrice de commutation modulaire est composée de cartes à 8 entrées et 8 sorties, permettant jusqu'à 32 entrées et 32 sorties, en vidéo numérique ou analogique large bande. Un bus vidéo interne diffuse les signaux provenant des entrées sur les diférentes sorties.
- la conversion de standard. Un signal 525 lignes est converti en 625 lignes.
- le formattage d'informations pour enregistrement de mission. Un signal vidéo standard est généré, et envoyé à un magnétoscope embarqué pour enregistrement. Il comporte un multiplexage temporel programmable par trame de 8 sources vidéo monochromes ou couleurs RVB, ainsi que des données numériques, marquées dans chaque trame.

3. ENREGISTREMENT DE MISSION

3.1. SYSTEME DE MULTIPLEXAGE TEMPOREL

Dans le système vidéo 625 lignes, le rythme de rafraîchissement des images d'une vidéo est normalement de 25 images par seconde (Stanag 3350 classe B). Partant des constatation suivantes:

- l'importance opérationnelle des images des différentes sources vidéo varie suivant les différentes phases d'une mission,
- certaines sources génèrent des images à vitesse de variation lente,
- les opérateurs de restitution font pour une grande part l'analyse d'images fixes sélectionnées,

s'il est acceptable à la restitution de visualiser des vidéos avec un mouvement légèrement saccadé, le multiplexage temporel réussit une excellente optimisation de l'utilisation de la bande passante d'un magnétoscope unique, en la distribuant à plusieurs sources vidéo.

La création d'une mosaïque de quatre sources est une mauvaise alternative, car le nombre de sources est fixe, et surtout la taille et la qualité des images est réduite.

Les fonctions de multiplexage temporel de plusieurs signaux vidéo et de marquage de données numériques dans la vidéo sont implantées sur une carte de l'équipement BISE.

Les sources vidéo dont les signaux peuvent être multiplexées sont celles disponibles dans l'avion, provenant de capteurs générant une image, de boîtiers générateurs de symbologie, ou des recopies d'écrans.

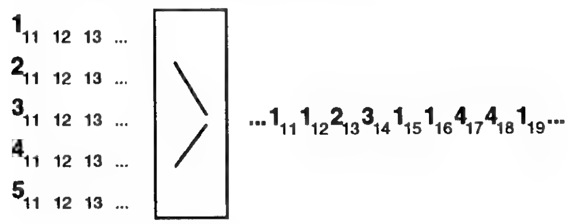
Description fonctionnelle

La carte permet de multiplexer temporellement, par trames ou images, huit sources trichromes RVB ou monochromes, suivant une séquence téléchargée de 32 pas maximum. Le signal vidéo résultant est généré avec un marquage numérique de chaque trame et des synchronisations vidéo reconstituées.

Fonctionnement

La carte possède huit entrées vidéo couleur RVB, externes avec protections ou internes au boîtier.

La séquence de multiplexage est de 32 pas maximum. Chaque pas définit le numéro de la source à transmettre, la durée d'une trame ou d'une image, le type monochrome ou couleur de cette source. Dans le cas d'une source monochrome, seul le canal vert est transmis en sortie.



Exemple de multiplexage de 5 sources, avec Images et Trames, à partir de la trame 11 - Séquence I 1, T 2, T 3, I 1, I 4

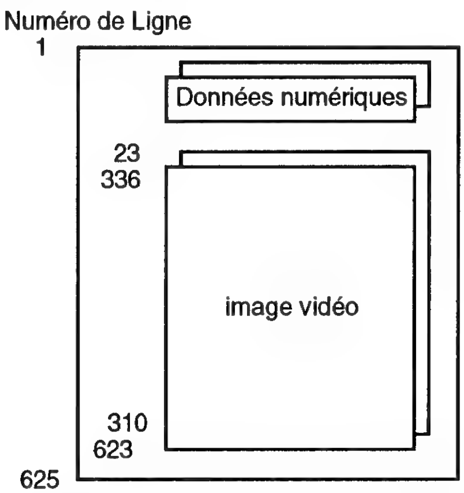
Le multiplexage temporel, la régénération des synchronisations et le séquencement du marquage sont réalisés en mode nominal à partir des signaux de synchronisation système générés par le BISE, ou en mode secours à partir de signaux extraits du canal vert d'une des huit sources. Les synchronisations des signaux incidents sont supprimées, bien que les signaux vidéo incidents soient normalement synchrones. La régénération des synchronisations permet d'envoyer au magnétoscope un signal totalement dépourvu de gigue.

Le signal vidéo est transmis en analogique avec une large bande passante, sans traitement ni dégradation.

Les données utilisées pour le marquage numérique sont celles nécessaires à la restitution de mission, soit le numéro d'identificateur de chaque source vidéo, l'heure système, un numéro d'avion et un numéro de mission. Elles sont programmées via le bus avion, ainsi que la séquence de multiplexage.

Ces données sont insérées dans le signal vidéo, dans quelques lignes inutilisées en début de trame, suivant le principe Télétexte. Le débit numérique nécessaire, de 40 bits par trame est faible. Le

marquage est réalisé par huits bits de données sur les lignes 10 à 15, avec des bits de synchronisations en début de ligne et un bit de parité en fin de ligne. La fréquence bit est faible, ce qui permet une grande robustesse de décodage au sol.



Marquage de chaque trame vidéo

Toute la logique de commande des fonctions de la carte est intégrée dans un composant logique programmable Xilinx 10 000 portes. Il comprend l'interface au bus numérique interne de commande, les mémoires de séquence et de données, le séquenceur, le compteur d'heure, un registre à décalage pour le marquage des données, l'asservissement des synchronisations vidéo.

Une évolution permettrait d'ajouter au marquage vidéo actuel d'autres données provenant des bus avion ou emports, à des débits plus élevés.

3.2. EVOLUTION VERS ENREGISTREMENT NUMERIQUE

Le système actuel d'enregistrement magnétique a les inconvénients de l'analogique:

- rapport signal/bruit,
- multitude des standards de codage couleur,
- gigue du signal enregistré suivant les contraintes mécaniques,
- exclusivité d'une bande magnétique pour un signal vidéo et un signal audio,
- mauvais interfaçage avec ordinateurs pour restitution numérique des images, nécessitant une conversion,
- dégradation de l'information lors de copies.

Un enregistrement magnétique numérique apporte des solutions. Il paraît intéressant de faire évoluer le système actuel vers un enregistrement numérique. Il est possible d'utiliser un enregistreur de la classe des 30 à 40 Mbits/s, moins encombrant et moins cher que les enregistreurs hauts débits de 100 Mbits/s et plus.

Le multiplexage temporel apporte une amélioration par rapport aux systèmes précédents d'enregistrement de mission, en permettant d'enregistrer plusieurs sources sur une seule cassette. Un enregistrement numérique doit permettre d'aller plus loin, en fusionnant les différents supports de données existant actuellement en une cassette unique. Cette cassette sera le support unique pour plusieurs signaux vidéos intégraux, signaux audio, données numériques, évènements ...

Les signaux vidéo nécessitent normalement une bande passante importante, 160 Mbits/s par exemple en 4:2:2. La compression vidéo, indispensable, est une technologie qui a muri. Les solutions sont de plus en plus intégrées, avec un coût en baisse constante.

Le type de compression (M-JPEG, MPEG1, MPEG2, ondelettes...) et le taux peuvent être programmés en fonction de l'intérêt de chaque source vidéo suivant la phase de mission. Certaines sources ont un contenu à variation de contenu lent, comme les écrans de symbologie. Elles peuvent être compressés en MPEG avec une très bonne qualité pour un débit très faible (2,5 à 3 Mbits/s).

Grâce à l'utilisation d'un support unique numérique, la restitution de mission sera facilitée, avec des informations accessibles rapidement, et déjà synchronisées.

4. RESTITUTION DE MISSION

La restitution de mission est une activité opérationnelle complexe. Nous décrivons un sous-ensemble permettant la restitution des signaux vidéo et données enregistrées sur une cassette vidéo. Celui-ci s'insère dans le cadre général d'un système de restitution de mission, permettant l'analyse opérationnelle. Le rejeu vidéo peut synchroniser le rejeu des données enregistrées dans l'avion sur les autres media extractibles.

Le matériel utilisé est du matériel faible coût, du commerce (COTS).

4.1. SYSTEME SOL DE DEMULTIPLEXAGE ET EXTRACTION DE DONNEES

La cassette vidéo une fois extraite de l'enregistreur embarqué de l'avion peut être utilisée au sol dans un lecteur non durci standard. Le signal vidéo peut être visualisé directement sur un moniteur vidéo. Lorsque la vidéo comporte un multipexage temporel de plusieurs sources, les images sont mélangées par l'œil. Une telle cassette n'est donc pas exploitable sans un équipement de démultiplexage temporel des différentes sources.

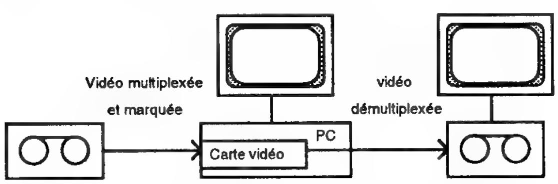
En sortie de l'équipement de démultiplexage, le mouvement perçu par l'opérateur dans le signal vidéo démultiplexé peut être légèrement haché, dépendant de la séquence de multiplexage programmée lors de l'enregistrement de mission pour cette source.

Description fonctionnelle

Le sous-ensemble de restitution vidéo et données développé pour la restitution du BISE réalise les fonctions suivantes:

- extraction des données numériques marquées dans chaque trame, avec contrôle de cohérence,
- démultiplexage d'une source vidéo sélectionnée par l'opérateur, avec mémoire d'image, ou affichage du signal vidéo d'entrée de manière transparente,
- affichage des données extraites par incrustation dans le signal vidéo de sortie,
- interface homme-machine pour affichage des données et sélection de la source à démultiplexer.

L'équipement de démultiplexage se compose d'une carte vidéo du commerce. Cette carte, au format ISA, est intégrée dans un ordinateur compatible PC.



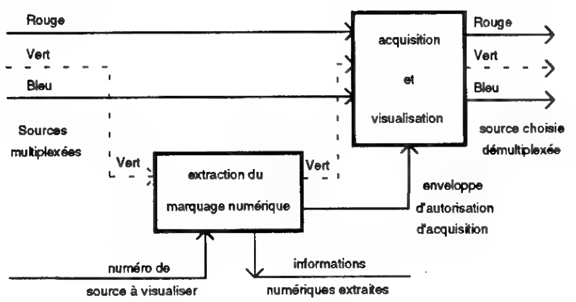
Cette carte comporte une entrée et une sortie RVB, six plans mémoire, un processeur DSP. L'entrée de la carte reçoit le signal d'un magnétoscope à sortie RVB, compatible du magnétoscope embarqué. La sortie de la carte est connectée à un moniteur. Le signal démultiplexé peut également être enregistré par un autre magnétoscope.

Un logiciel Windows exécuté par le PC assure l'interface homme-machine. L'opérateur peut ainsi sélectionner la source vidéo à visualiser parmi celles existantes dans la vidéo multiplexée en entrée. Les fonctions principales du magnétoscope peuvent être télécommandées.

Il est possible de démultiplexer plusieurs sources simultanément, en intégrant plusieurs cartes dans le PC. Le démultiplexage de 4 sources a été validé. Les quatre images sont envoyées en parallèle sur quatre moniteur vidéo. Une mosaïque en quatre quarts d'écran peut également ête constituée sur un seul moniteur.

Fonctionnement

Les différentes fonctions sont assurées en temps réel par le processeur DSP de la carte. Le processeur du PC n'a pas besoin d'être puissant, et est disponible pour le logiciel Windows. Des paramètres transmis par ce logiciel Windows en fonction du choix de l'opérateur indique au DSP son mode de fonctionnement, transparent ou démultiplexage, et dans ce cas le numéro de la source à démultiplexer.



Les contraintes mécaniques subies par l'enregistreur embarqué entraînent des déphasages importants des synchronisations vidéo lors de l'enregistrement du signal. La carte d'acquisition s'asservit sur le signal en lecture pour compenser cette gigue.

La méthode retenue pour l'extraction des données est originale, et entièrement numérique. Elle utilise les ressources de la carte d'acquisition vidéo.

A chaque trame incidente, les ligne 10 à 15 sont numérisées dans une zone de la mémoire d'image. Pour chaque ligne, le DSP réalise en temps réel le seuillage du niveau des quelques pixels correpondant à chaque bit numérique marqué, après calage temporel sur les premiers bits de synchronisation. Les 6 octets numériques transmis sont ainsi reconstitués et accumulés dans un buffer. Le buffer est transmis au logiciel Windows, qui peut l'afficher et le stocker sur disque.

Dès la ligne 16, le DSP compare le numéro de source transmis dans cette trame avec celui sélectionné par l'opérateur. Si le numéro est

différent, le DSP attend la trame suivante sans rien faire. La mémoire de visualisation est inchangée.

Si le numéro de cette trame correspond à celui sélectionné par l'opérateur, le DSP déclenche l'acquisition du contenu vidéo de la trame sur les trois plans RVB directement dans la mémoire de visualisation.

Le signal vidéo en sortie est synchrone du signal d'entrée. Le contenu du signal de sortie correspond à celui de la mémoire d'image. Lorsqu'il est configuré en mode transparent, ou qu'une vidéo sans marquage numérique lui est envoyé, le signal de sortie est identique au signal d'entrée.

4.2. EVOLUTION MULTI-APPAREILS MULTI-OPERATEURS

La complexité des missions va en augmentant. Plusieurs appareils sont en général engagés ensemble. Une restitution de mission assurant le rejeu de mission d'un seul appareil entraîne des limitations.

Un nouvel ensemble devrait être développé, pour permettre l'exploitation synchronisée des données de mission de plusieurs appareils en patrouille, simultanément par plusieurs opérateurs indépendants.

De même que l'enregistrement de mission devrait évoluer vers un enregistrement numérique, une restitution vidéo numérique présente des avantages.

Description fonctionnelle

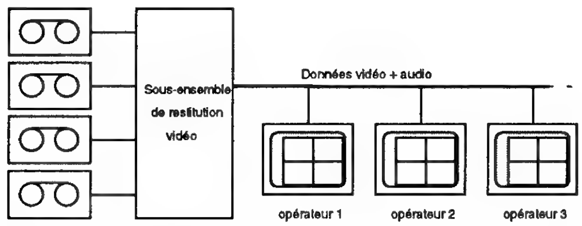
Le sous-ensemble de restitution vidéo permet de lire jusqu'à quatre cassettes vidéo simultanément. Il pilote les quatre magnétoscopes de manière synchrone, ce qui permet de visualiser les vidéos de plusieurs avions synchronisées sur une même heure. Il est ainsi possible de faire une analyse de mission d'une patrouille d'appareils.

Chaque cassette vidéo peut comporter un multiplexage temporel de sources vidéo embarquées, jusqu'à huit sources. Chaque opérateur peut visualiser par démultiplexage temporel un des huit signaux vidéo de chacune des quatre vidéo sur son écran informatique, ou jusqu'à quatre vidéo simultanément, sous forme d'une mosaïque de quatre quarts. Ces quatre signaux sont alors choisis indépendemment par chaque opérateur parmi les 32 signaux capteurs enregistrés dans les avions.

Chaque cassette vidéo peut également être exploitée de manière indépendante, non synchrone, par un ou plusieurs opérateurs. Plusieurs opérateurs peuvent ainsi réaliser simultanément l'analyse de missions différentes.

Fonctionnement

Les postes opérateurs sont connectés au sous-ensemble de restitution vidéo. Ils lui envoient leurs commandes pour le pilotage des magnétoscopes, pour le rejeu de cassettes en mode synchronisé ou indépendant.



Le sous-ensemble vidéo asservi les magnétoscopes. Les signaux vidéo et audio de chaque magnétoscope sont numérisés. Les données de mission marquées dans chaque trame vidéo sont extraites.

Chaque opérateur sélectionne indépendamment des autres un à quatre signaux vidéo qu'il veut restituter en mosaïque, et une voie audio.

Cette architecture offre de multiples avantages:

- les signaux issus des quatre magnétoscopes et sélectionnés sont diffusés sous forme numérique aux opérateurs,
- les informations sont numérisées une seule fois. Il n'y a pas de dégradation du signal due à des conversion successives. La qualité de la chaîne numérique est supérieure à celle des magnétoscopes analogiques,
- le moniteur de visualisation de la station opérateur assure une visualisation non entrelacée à haute fréquence, ce qui assure une meilleure efficacité et une moindre fatigue oculaire que la visualisation directe d'une vidéo entrelacée,
- l'évolution pour un interfaçage avec des enregistreurs numériques haut débit est facilitée, la vidéo étant déjà traitée en numérique.

5. AUTRES MODES DE RESTITUTION

Alors que le pilote est seul pour assurer sa mission, l'exploitation des données est réalisée en équipe.

Dans certains cas, ces équipes souhaitent récupérer les données immédiatement. Lorsqu'elle est possible, une transmission hertzienne temps réel le permet.

Dans d'autres cas, le pilote peut souhaiter avoir lui-même accès à certaines données pour prendre une décision quant au déroulement de sa mission. Ces données doivent être stockée, en parallèle de l'enregistrement de mission, dans un boîtier embarqué avec une mémoire consultable sans délai.

5.1. TRANSMISSION TEMPS REEL

La transmission hertzienne permet une exploitation de mission en différé immédiat, sans attendre le retour des appareils. Les données peuvent être utilisées pour la préparation d'une nouvelle mission, qui peut ainsi démarrer plus tôt.

Différents matériels existent, équipements bord et sol (émetteur, amplificateur, antenne fixe ou pointée, récepteur), pour une transmission numérique ou analogique, dans différents spectres (400MHz, 2,5 GHz, 15 GHz, étalé...).

5.2. EXPLOITATION DANS L'AVION EN REJEU IMMEDIAT

Le concept d'un équipement d'acquisition et restitution vidéo immédiate est en cours d'étude.

Lors du déroulement d'une mission, le pilote s'en tient, autant que possible, au plan de vol et aux actions prévus. Lors de certaines missions, avec impératif de destruction par exemple, il peut être nécessaire d'effectuer un deuxième passage.

La visualisation en différé immédiat de l'enregistrement de la vidéo d'un capteur (par exemple pod de de désignation laser PDL), avec fonctions pause / avant / arrière, facilite l'évaluation des dommages et permet une décision locale de faire ou non un second passage.

Ce type de fonction est également extrêmement efficace pour l'entraînement des pilotes.

Le boîtier d'acquisition et restitution vidéo immédiate numérise un signal vidéo et le stocke dans une mémoire, après compression vidéo numérique. L'enregistrement en mémoire est réalisé en tambour, avec une autonomie de stockage de quelques minutes. L'acquisition peut être stoppée pour préserver le contenu.

L'utilisation de ce boîtier est indépendante de l'enregistrement de mission, qui peut enregistrer le même signal en parallèle. Ainsi les dernières minutes écoulées peuvent être revues à tout instant, sans perturber l'enregistrement de mission, ni conditionner l'exploitation qui sera faite au sol.

Lors de la demande de rejeu, la visualisation du signal est immédiate, sans cassette magnétique à rembobiner. Les fonctions habituelles de pause, avance avant/arrière sont disponibles. Le stockage numérique permet le rejeu des images de nombreuses fois avec la même qualité.

Des données peuvent être enregistrées simultanément, et restituées incrustées dans l'image.

Après exploitation en vol, il n'est pas nécessaire de conserver les images en mémoire. L'exploitation complète de ce signal vidéo peut être réalisée au sol à partir de l'enregistrement de mission.

L'architecture du boîtier fait en partie appel à des composants du commerce disponibles en gamme de température industrielle. L'ensemble est durci pour répondre aux contraintes de l'environnement embarqué.

Il se compose des sous-ensembles suivants:

- un boîtier avec fixations et interconnexions de commande, entrée vidéo, sortie vidéo,
- alimentation,
- carte unité centrale, pour gestion des commandes, des données bus et du débit vidéo numérique,
- carte d'interface au bus de données,
- carte de compression / décompression vidéo temps réel, avec conversions analogique / numérique et inverse,
- cartes mémoire, de capacité configurable suivant la durée d'enregistrement nécessaire.

L'ensemble se contente de moins d'un litre et moins d'un kilo.

Le boîtier peut être configuré pour un signal vidéo 625 lignes (PAL) ou 525 lignes (NTSC). La compression est réalisée en temps réel, trame à trame, suivant la norme M/JPEG.

Cette fonction pourrait être incorporée dans un boîtier existant, de distribution vidéo ou

d'enregistrement de mission, pour limiter les interconnexions et les redondances de type boîtier, alimentations...

Lorsque l'enregistrement de mission embarqué sous forme numérique sera une réalité, le support pourra être de la mémoire en remplacement de la bande magnétique. La fonction de restitution immédiate pourra alors être intégrée à moindre coût, en ajoutant simplement une décompression temps réel et une sortie vidéo, et en utilisant les données existantes dans la mémoire de l'enregistreur de mission.

6. CONCLUSION

SAGEM S.A. a développé un équipement embarqué dont une des fonctions est le multiplexage temporel avec marquage, ainsi qu'un sous-ensemble sol qui réalise le démultiplexage vidéo et l'extraction des données numériques.

Les enregistreurs magnétiques doivent être placés dans la cabine de pilotage, pour la tenue mécanique et l'accessibilité. La diminution du volume nécessaire dans cette zone est essentielle. Le multiplexage temporel apporte une amélioration par rapport aux systèmes précédents d'enregistrement de mission.

La possibilité d'enregistrer jusqu'à huit sources vidéo en les gardant exploitables, la réduction globale du coût et de la masse sont autant d'avantages décisifs de cette architecture.

Les évolutions prévisibles de cette architecture sont:

- une exploitation locale avec rejeu immédiat embarqué, en vidéo numérique,
- un enregistrement de mission numérique multi-données sur un media unique,
- une restitution de mission multi-appareils, multi-opérateurs, multi-données, en vidéo numérique,
- une augmentation de l'intégration des fonctions, dans un nombre plus faible de boîtiers embarqués.

L'augmentation de la complexité des systèmes va de pair avec l'augmentation de l'intégration des équipements. Le nombre croissant de fonctions, dans un nombre d'équipements embarqués en baisse, nécessite que leur développement soit conduit par des sociétés maîtrisant l'ensemble des compétences fonctionnelles.

SAGEM S.A. maîtrise la chaîne complète de préparation, enregistrement et restitution de mission.

A GENERIC ARCHITECTURE FOR CREW ASSISTANT SYSTEMS

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1. INTRODUCTION

A crew assistant is an on-board automated system that supports an aircraft crew in performing its tasks. Aircraft crews are currently confronted with numerous displays and complex controls in their cockpit. An overwhelming amount of multi-source data is offered while simultaneously control over the aircraft and its systems has to be maintained. This may lead to situations of high workload in which non-optimal decisions are made.

Crew assistant systems are planned to reduce this problem and hence improve efficiency and flight safety. They are expected to rely heavily on Advanced Information Processing (AIP) technologies to organise data and control flow in such a way that the crew is provided with concise and relevant information. At the same time the crew's control efforts will be considerably reduced. This will enable the crew to concentrate on essentials and to make decisions more effective.

Several developments exist in this area. Pioneer programmes are the US "Pilot's Associate"[1], the British "Mission Management Aid"[2], the French "Copilote Electronique"[3] and the German "Cockpit Assistant System"[4]. These programmes go by different names but all aim at the automation of routine tasks and the provision of effective aids to the crew in problem solving and task management. The architectures developed in these programmes have many elements in common but suggest a more generic architecture. Another common element of these programmes is that they consider AIP as key technology for their successful implementation. AIP provides technologies able to handle the complex interaction between crew, crew assistant, aircraft systems and sensors.

This paper* focuses in particular on these two aspects: a generic crew assistant architecture and the application of AIP technology. In section 2 the operational environment is described in which a crew assistant is to be embedded. Section 3 introduces a generic crew assistant architecture which is independent of any type of aircraft or operation. Section 4 proposes the application of AIP in general and of multi-agent systems in particular as a key technology for successful implementation of a crew assistant. Throughout the paper, the crew assistant is illustrated by an application of a single-pilot military aircraft, but the concept is also relevant to multi-crew or civil aircraft.

2. OPERATIONAL ENVIRONMENT

2.1. Introduction of crew assistant

The main task of any aircraft crew is to operate its aircraft to attain its military mission or civil flight objectives. In the traditional situation, each aircraft system and sensor will interface directly with the crew through dedicated controls and displays in the cockpit. The crew has to interpret multiple displays and has to operate multiple controls simultaneously in order to perform the functions that are related to its main task. In the non-assisted, traditional situation, the interpretation of all sensor information and the control of all

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The examples in this paper are based on results of EUCLID CEPA-6 RTP 6.5 "Crew Assistant", a cooperation between The Netherlands (NLR), Germany (DASA), Italy (Alenia) and Turkey (Boğaziçi Üniversitesi). The objective of this RTP is to realise a concept demonstration to show that a crew assistant for military aircraft meets the needs of future operational missions and improves mission capability in a cost-effective manner.

Paper presented at the AGARD MSP Symposium on "Advanced Architectures for Aerospace Mission Systems", held in Istanbul, Turkey, 14-17 October 1996, and published in CP-581.

systems remain with the crew. A typical example is an "oil pressure warning" on the cockpit system panel which may indicate an oil pressure malfunction. The crew has to confirm this hypothesis by considering oil pressures at a variety of engine power settings indicated in its checklist. Once this hypothesis is confirmed, the crew has to adjust the engine power to delay further system breakdown, search for the cause of the malfunction and meanwhile replan the routing to a recovery base in order to land as soon as practical.

The upward arrows in the traditional situation (left diagram in **figure 1**) illustrate the information flow from sensors to the displays, downward arrows illustrate the control flow to the systems. For reasons of functional consistency, the cockpit elements are divided into displays (inputs from sensors to the crew only) and controls (output from the crew to systems only). The aircraft elements are divided into sensors (output to displays only) and systems (input from controls only). In reality, most cockpit and aircraft systems will integrate these functional elements.

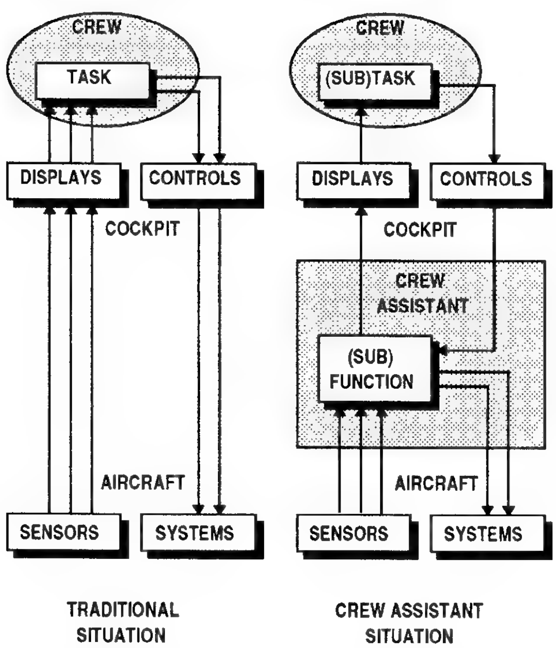

Figure 1: Crew assistant operational environment

The right diagram illustrates the situation when (a part of) a crew task is assigned to a crew assistant. The original task is then split into a (sub)function delegated to the crew assistant and a (sub)task that remains with the crew. Depending on how much of the original task is delegated to the crew assistant, this will result in a change in the amount of information offered to the crew and in a change in the amount of control required from the crew. In the "oil pressure warning" example, a crew assistant could confirm that the warning is indeed caused by an oil pressure malfunction and, depending on authorisation by the crew, the crew assistant could execute corrective actions. In addition the crew assistant could propose and prepare routing to the nearest recovery base.

Figure 1 is the basis for further discussion in this paper. The external elements (crew, tasks, cockpit and aircraft elements) will be described in this section and the crew assistant will be the subject of the next sections.

2.2. The crew

The number of cockpit crew members may vary from a single seat military fighter to 3-4 members of a commercial airliner crew. The situation of a single-seat fighter aircraft is considered to place the most severe requirements on a crew assistant. The situation of a multiple member aircrew (military transport or civil) is less demanding but may have additional and specific requirements. The commercial need in civil aviation for reduction of crew members, has already led to the introduction of a number of operational crew assistant realisations. A typical example is the Electronic Centralised Aircraft Monitoring (ECAM) system on-board the Airbus-300 family of aircraft[5].

The difference between a military and a civil application will provide the designers of crew assistant system with an interesting design dilemma. It is essential for military operations, and especially for tasks that are related to tactics, that military pilots are trained to be "unpredictable". This implies that military crew assistant functions which require modelling or monitoring of pilot behaviour are difficult to define. In civil aviation, on the other hand, pilots behave more predictably and monitoring pilots behaviour is an attractive area for crew assistant research and applications[4].

2.3. The tasks

The aim of a crew assistant is to provide the crew with an improved system and situation awareness and to enable the crew to make the best possible decisions in any situation. When analysing different crew tasks to be supported by a crew assistant, it is attractive to decompose these tasks into several levels of hierarchy and complexity. The hierarchy between these levels is that the crew will only pay full attention to the next level once all tasks allocated with the previous one are handled adequately. Going from one level to the next level, the attention span of the crew enlarges and the amount of information to be processed increases considerably. These tasks levels are:

- the ***aviate*** level which includes all tasks related to handling the aircraft, to basic flying and manoeuvring, to monitoring system health and status, and to encountering system malfunctions and emergencies;
- the ***navigate*** level which includes all tasks that keep the aircraft on the intended (navigational) mission or authorised (air traffic) flight plan;
- the ***communicate*** level which includes the tasks that coordinate with all friendly elements that contribute to or may interfere with mission or flight intentions;
- the ***operate*** level which includes the tasks that deal with all unfriendly entities that directly interact or will have effect on the successful mission completion.

The workload during a mission or flight is dependent on the amount of tasks at the highest level, which may be very different for a military mission and a civil flight. For a military mission the tasks at the "operate" level (eg. attack phase) represent the highest workload and will occur in the middle of the mission. For a civil flight the tasks at the "communicate" level, during approach and landing at the end of the flight, normally represent the flight phase with the highest workload.

The introduction of operational crew assistant systems will start with routine tasks at the "aviate" level. Traditional autopilots (altitude/heading/attitude-hold) were already introduced in the early-50s and can be considered first crew assistant systems that relate to the basic flying tasks of the "aviate" level[6]. Expansion of autopilot support to the "navigate" level was common on most civil airliners before 1980[7]. The research systems Assistant for Single Pilot IFR Operation (ASPIO, 1991) and Cockpit Assistant System (CASSY, 1995) monitored the execution of a civil flight-plan and apply to both the "navigate" and "communicate" level[8]. Typical military examples are the Joint Tactical Information Distribution System (JTIDS, first delivered in 1993) and the Multi-function Information Distribution System (MIDS, still under development and designed to fit smaller fighter aircraft). These systems provide secure voice communication and tactical digital information links, and apply to both the "communicate" and "operate" level[9]. Most complicated are military applications that are designed to support the 'operate' level. Typical examples here are the self defence mission aids in development for the next generation fighters which aim to support electronic warfare tasks.

2.4. Cockpit displays and controls

When adding crew assistant to support different crew tasks, the interaction between crew and crew assistant depends heavily on the available display and control interfaces in the cockpit. Contemporary cockpits reveal a blend of display and control technologies, ranging from conventional electro-mechanical dials to flat-panel colour displays and from mechanical switches to voice-controlled input devices.

By far the greatest majority of displays use vision although audio signals are used to provide alerts in danger or failure situations. Modern displays use fast computer processing and graphic symbol generators to convert sensor information into digital data for presentation on either head-down, head-up or helmet-mounted displays. Because these displays can be adapted to display almost any type of information, they became Multi Function Displays (MFD) which enables efficient use of cockpit space, especially in a front panel location.

Cockpits incorporate a variety of mostly manually operated controls. Recent developments might allow voice to be exploited for control purposes but recognition rate, response time and input error rates do not match those of manual keyboard entries. Visual controls and in particular helmet mounted pointing sights are operational in state-of-the-art Russian fighter aircraft. The field-of-view for target designation is much wider than conventional pointing devices and allows full exploitation of the off-boresight capability of modern guided weapons. Major disadvantages are the weight of the current generation sights and their unreliability at high g-load factors.

By far the greatest majority of controls are still manual and they can be located anywhere in the cockpit, provided the pilot can reach them. The hands-on-throttle-and-stick (HOTAS) concept that is pursued in almost all military fighters collocates important switches with the flight controls. Cockpit front panels, quarters panels and side consoles are traditionally crowded with singular switches, rocker switches, push buttons, rotary switches and joysticks. Each of these was originally assigned to a single system function. Multi-function controls are possible by adding arrays of push buttons to an MFD. A variety of controls are possible by displaying their active input function.

Because of their flexibility and capability to support complex (display and control) communication, MFDs are expected to play a major role in crew assistant applications. Some psychologists and human factors experts praise MFD's capability to present information and to reduce pilot's workload. Others expressed warnings of potential information overload eg.: "the F-18 cockpit has three cathode-ray tubes and a head-up display; there are 675 acronyms and 177 symbols which can appear in four different sizes on any of the

three cathode-ray tubes; there are 73 threat, warning and caution indicators, 59 indicator lights, and 6 warning tones, 10 multi-function switches on the throttle, 7 on the stick, 19 controls on the panel underneath the head-up display, and 20 controls around the periphery of each of the three cathode-ray tubes, each of which has a multi-switch capability"[10].

2.5. Aircraft sensors and systems

The primary task of any aircraft crew is to operate its aircraft and to employ its sensors and systems in order to attain its mission (or flight) objectives. When considering a crew assistant to support the crew in performing this task, the aircraft sensors and systems that play a role can be divided according to the different task levels of section 2.3.

Sensors and systems to aviate. The aviate task is to keep the aircraft airborne and includes basic flying and system health monitoring. Main sensors and systems are the aircraft attitude (pitch-, roll-, and yaw-angle) sensors and the flight controls, closely linked with engine performance sensors and control. Current status of automation already provides basic autopilot functions and engine performance optimisation during different flight phases (take-off, climb, cruise). Additional systems included in the aviate task are flaps, slats, dive brakes, drag chute, landing gears, aircraft support systems (electrical power, fuel, hydraulics) and life support systems (oxygen, etc). These systems are not expected to play a role in crew assistant applications because they are already self-contained and mostly fully automated.

Sensors and systems to navigate. Navigation comprises 3-dimensional routing and timing of an aircraft such that it reaches pre-defined positions at pre-defined times. This task can only be executed with sufficient knowledge of present position and existing restrictions as contained in air traffic control procedures and flight plan. Military operations are supplemented with a variety of time and position dependent restrictions. Various state-of-the-art automation supports navigation along a horizontal and vertical flight path (eg. autopilots for VOR interceptions or ILS landings), or are controlled by a Flight Management System (FMS). It is expected that, by the year 2000, satellite based navigation (GPS) will be the prime navigation aid for the en-route, terminal, non-precision and precision approach phases of flight. Present ground based navigation aids will be gradually phased out and GPS-INS embedded systems will provide a uniform concept with unprecedented accuracy for automated navigation support during the entire flight.

GPS is also a cornerstone technology of the free flight concept which envisaged that air traffic control systems would allow individual aircraft to utilise their own direct routing and air traffic separation. Both navigation and air traffic control are candidate areas for crew assistant developments.

Sensors and systems to communicate. Communication includes two-way verbal communication between aircraft crew and other entities, systems for identification (IFF/SIF), and tactical target and data links. The most suitable area for crew assistant support is verbal communication, especially during flight phases with a high workload (approaches under air traffic control) or during mission phases that are critical for successful mission accomplishment (ground controlled intercepts or ground directed attacks).

Sensors and systems to operate. The operate task refers to military roles. Aircraft sensors and systems that support these roles vary much dependent on the specific demands from their operational environment: eg. air-to-air defence, air-to-ground attack, defence suppression, airborne surveillance or airborne command and control. Consequently, candidate tasks for crew assistant support are manifold and range from target acquisition and weapon management to situation assessment and self defence.

3. FUNCTIONAL ARCHITECTURE

The previous section defined the operational environment of a crew assistant and described its complexity. A crew assistant will help the crew operate in this environment and will even hide some of the complexity from the crew. This section presents the functional architecture of a crew assistant and describes how the crew assistant will interface with this operational environment.

The functional architecture (see **figure 2**) is based on a modular, horizontal and vertical, decomposition. The crew assistant can be seen as a collection of relatively independent functions that assist the crew in different tasks and hence will require different capabilities. The crew assistant can also be seen as a data processing unit that processes low-level data in several stages from aircraft sensors up to easy-to-assess information to be displayed to the crew.

Coordination and interfacing between the crew assistant and the crew, and between the crew assistant and aircraft cockpit elements, will be allocated to four additional interface management modules.

3.1. Functions

The crew assistant functions directly support crew (sub)tasks. Ideally single crew assistant functions may correspond with single crew tasks. It is also possible that the crew assistant includes modules of multiple functions supporting strongly related (sub)tasks. This separation into functional modules will aim at a maximum internal coherence within one functional module and at a minimum interaction between different modules. The modules are at the same hierarchical level which results in the first (horizontal) decomposition of the architecture (see **figure 2**).

Typical military tasks to be supported by a crew assistant were identified during EUCLID RTP 6.5. Interviews were conducted with 33 pilots from air forces of the participating nations, flying the F-16, MRCA and AM/X. Reference missions (air-to-air and air-to-ground) were defined. Key criteria for task identification were their operational relevance, their impact on pilot workload and mission effectiveness and the expected applicability of AIP technologies[11]. The following typical tasks were identified:

System management: addresses monitoring of normal system performance (and in particular engine performance), trend analysis, and reporting of information on system status.

Malfunction handling: relates to analysis of anomalies, to presentation of appropriate warnings, to (checklist) assistance in countering malfunctions, and (when authorised) to automatic execution of corrective actions.

Mission/flight planning: includes the capability to monitor mission/flight progress, to evaluate the impact of environmental entities (eg. adverse weather and enemy threats) on this plan and, if needed, to assist in or to perform an automatic (re)planning.

Situation awareness: relates to the capability to combine and interpret all available environmental data in order to derive an easy to assess situation picture of this environment; situation awareness may be limited to navigational information but, for military applications, includes all relevant strategic and tactical information.

Self defence: addresses management of self protection systems, assessment of sensor information, selection of available countermeasure options, and (automatic) execution of the selected tactics.

3.2. Data processing levels

For each crew assistant function, the basic flow of data is from the aircraft sensors to the cockpit displays. It is the goal of a crew assistant to direct this flow by processing aircraft sensor data into information for display. The main objective is to provide the crew with concise and relevant information. In this process, a number of steps can be distinguished, each representing a processing level at which data are combined with information, knowledge and procedures and interpreted into information for a next step. Four processing levels are distinguished (see **figure 2**): collection, assessment, decision and presentation.

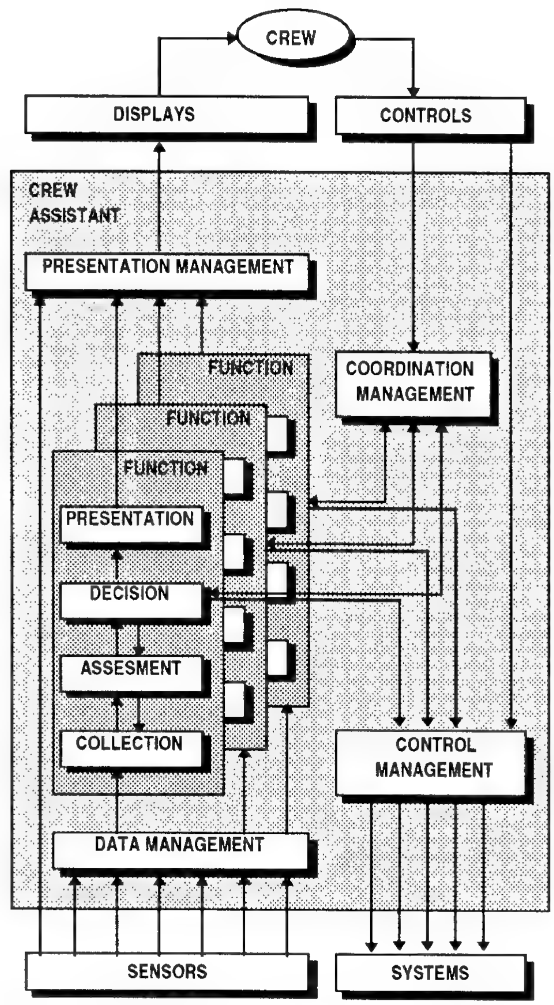

Figure 2: Functional architecture of crew assistant

At the ***collection*** level, data are collected and prepared for further assessment. This includes:

- the collection of data from sensors and other input devices on-board the aircraft,
- the transformation of these data into a format that can be read by the assessment level,
- the execution of complex operations in which data from different sensors are integrated into a standard data format (eg. by sensor data fusion),

- the preliminary filtering of data by rejecting irrelevant data or by giving priority to data that are urgently needed by higher processing levels.

At the ***assessment*** level, the collected data are assessed on normal or abnormal properties. This includes:

- the comparison of data from the collection level, mutually or by comparison with reference data (eg. threshold values),
- the execution of complex processing, eg. the analysis of system trends by examining a range of chronological data values and the prediction of values in order to anticipate future problems,
- the assessment of the aircraft environment on the basis of sensor data.

At the ***decision*** level, it is decided what has to be presented to the crew on the basis of inputs from the assessment level and possibly provide autonomous control. This includes:

- the filtering of data from the assessment level in order to prevent saturation of the crew's cognitive resources,
- the generation of advice on handling abnormal situations,
- if authorised, the execution of autonomous action, i.e. control the aircraft systems.

Finally, at the ***presentation*** level, it is decided how the information from the decision level is presented to the crew. This includes:

- an assessment of the available cockpit display resources and crew preferences,
- the presentation of information in such a way that the crew is directly cued and able to process the information efficiently and effectively.

Each processing level has a characteristic combination of type of data, information, knowledge and operations. These levels communicate with each other hierarchically and result in the second (vertical) decomposition of the architecture (see **figure 2**). Inputs from a higher level are intended for control or request for information. The lower level is obliged to act according to this input. Conversely, inputs from lower levels are intended to be information only. A higher level is free to process this input. The decision level is modelled to be the only level that receives external coordination from the crew and it is the only level that provides control to aircraft systems. Crew coordination includes preferences for display presentation and authorisation to the crew assistant to control aircraft systems.

The different levels of data processing within the crew assistant show similarity with the hierarchical model and processing levels proposed for C^3I data fusion[12]. The main difference is that the data fusion process specifically supports situation and threat assessment within a C^3I application while the crew assistant process will support a variety of crew tasks, including situation and threat assessment.

3.3. Interface management

Crew assistant externally interfaces with displays and controls in the cockpit and with sensors and systems on-board the aircraft. The crew assistant functional architecture adds capabilities to organise the corresponding data, information and control flows. These capabilities are organised in four interface management modules (see **figure 2**): coordination, control, data and presentation management. Different aspects of interface management will be discussed in the next sections.

3.3.1. Coordination management

Crew assistant authority. By delegating a task to the crew assistant, the crew inevitably has to specify the nature of its interaction and the authorisation for presentation and control. This delegated authority can be expressed in standard levels of automation (eg. stand-by, manual, semi-automatic and automatic). Full automation is outside the scope of the crew assistant and in the "automatic" mode the crew assistant should at least inform the crew on the status of its activities and should instantaneously accept a reset by the crew at any time. The crew should have a correct and complete understanding of the functioning of the crew assistant in all modes, in order to allow a smooth transition between different modes and to maintain consistency with manual (non crew assistant) operations. The crew remains in the loop and may regain control at any time.

Coordination between functions. When several tasks are delegated to crew assistant, interactions will take place which require coordination between the corresponding functional modules. This includes:

- translation and decomposition of the request for assistance by the crew into the activation of all needed functions within the crew assistant;
- prioritisation between crew assistant functions when simultaneous execution of crew assistant functions results in conflicts that are related to the crew (limited cognitive capabilities), to the aircraft (limited available cockpit displays or supporting sensors) or to other resources (computer memory, processing power or throughput capability);

- cooperation between crew assistant functions when some functions need specific results from another; this control (or request for data) is performed at the decision level though the actual exchange of data may remain at the assessment level.

3.3.2. Control management

Overruling by the crew. For each function that is delegated to the crew assistant, the crew shall be able to overrule the crew assistant. Overruling may cause sensors and systems to receive control inputs from both the crew and crew assistant which may be conflicting. This conflict is prevented within the design of the crew assistant by routing all control inputs through a control management module. Note that overruling of system control is basically different from de-selecting crew assistant.

Conflicting system control. A conflict in system control exists when the same aircraft system is employed simultaneously both by the crew and crew assistant while each performs a different task. This occurs when eg. the crew assistant performs a mission planning function and directs a radar in its ground mapping mode while simultaneously the crew selects that radar to operate in an air-to-air mode. Control management prioritises and solves such conflicts and, when required, informs the crew and requests additional guidance.

When multiple functions are assigned to the crew assistant, these may also conflict in controlling the same systems. This may occur when eg. (short term) self defence functions and (long term) mission planning functions simultaneously request the same sensor to provide information. Solving these conflicts has to match the way the crew would solve them.

Crew requested input. Occasionally, the crew assistant may not be able to collect all data required to perform a function, eg. because a sensor is malfunctioning or because there is no sensor available. Such data can be obtained by requesting the crew to provide them. Loading mission data via a crew inserted data cartridge is part of this capability.

Sensor management. When data collection requires activation or redirection of a sensor, this control is subject to crew authorisation and does not differ from control of other systems. Control management, therefore, should include sensor management.

3.3.3. Data management

Importing sensor data. Data management is responsible for importing and filtering all sensor data as required by the active crew assistant functions. One function might require data from multiple sensors while other functions might require data from the same sensor. Data management is responsible for correlation of filtered data with the crew assistant internal data. It is expected that data management and data collection will be closely integrated in the system design of a crew assistant.

Sensor data fusion. Data management is closely related to sensor data fusion, but the overall sensor data fusion problem should be resolved outside the crew assistant. The functional architecture assumes responsibility for correct data to remain with each sensor individually and the responsibility for correctly fused data with the involved sensors collectively.

3.3.4. Presentation management

Limited display resources. The crew assistant will be operational in a cockpit environment that is expected to rely heavily upon MFD technology. This implies that conflicting requirements in the presentation of information are likely to emerge when multiple crew assistant functions simultaneously require access to the same display. Solving these conflicts has to match the way the crew would solve them. Remaining conflicts should be prioritized and, when required, additional guidance should be requested from the crew.

The crew assistant may also be in conflict with a sensor not involved with crew assistant if both require the same display in the cockpit. Since such a conflict emerges by the introduction of a crew assistant, it should be solved by the crew assistant. The conflict could also be solved by displays that are dedicated only to the crew assistant.

4. ADVANCED INFORMATION PROCESSING

The crew assistant architecture presented shows a modular approach in which various functional elements can be marked as knowledge intensive. It also shows that crew assistant interactions are complex and that these interactions should remain transparent to the crew at all times. Advanced Information Processing (AIP) provides technologies able to handle this complexity and support a sophisticated man-machine interaction by minimising the cognitive gap between man and machine. Candidate AIP technologies are:

- knowledge-based systems,
- natural language and speech understanding,
- perception, including advanced sensor data processing and fusion,

- planning, eg. for in-flight mission planning,
- learning to improve crew assistant capabilities,
- distributed problem solving.

This section will focus on how to realise a crew assistant system architecture. The features of AIP technologies that are required to provide a firm basis for a crew assistant system architecture are reviewed first. It is further argued that distributed problem solving, and in particular multi-agent systems, are proper AIP technologies for the crew assistant overall system architecture while other technologies might be applicable to specific elements within this system architecture.

4.1. Requirements for AIP applications

The AIP technologies that will be applied to develop the crew assistant functional architecture into a system architecture should have features that satisfy the following design requirements:

Modularity. The crew assistant shall be based on technologies that allow logical decomposition of the system into smaller components (modules) with well-defined interfaces. Modularity facilitates development, enables future upgrades and reduces life-cycle costs by improved maintenance.

Real-time performance. The crew assistant shall have guaranteed response times in a highly dynamic environment. It may be better to provide an acceptable response in time than to provide a response that is best, but too late. This can be extended with the requirement for a response being not too complex. Although a complex response is in time, its contents might be difficult to understand. Real-time performance is a critical factor in crew acceptance.

Reliability. The crew assistant shall have built-in hardware and software elements that are designed to reduce the risk of a complete system failure. The applied technologies should allow for a graceful performance degradation in case of failure.

Integration. The crew assistant includes many diverse functions needing different implementation methods and techniques. The technology used should support integration with conventional as well as advanced methodologies preserving modularity.

System engineering. The crew assistant shall be developed and maintained by a well-defined and widely-accepted system engineering methodology. The technology used should support such a methodology in order to reduce development and life-cycle costs.

Maturity. The crew assistant shall be based on mature and proven implementation technologies. This is expressed by the availability of tools, successful prototypes and operational applications.

4.2 Distributed Problem Solving

An emerging candidate technology for realisation of the crew assistant system architecture is Distributed Problem Solving (DPS)[13]. This technology provides a natural transition from the crew assistant functional architecture to a system architecture where the inherent distribution and modularity of functions is preserved in the functionally-distributed problem solving modules.

DPS technology considers two main approaches: distributed knowledge sources (often referred to as blackboard systems) and multi-agent systems. Both consist of multiple agents but they differ in structure at global architecture level and at agent level. A multi-agent system normally consists of heterogeneous agents that have a range of expertise or functionality (eg. a complete knowledge-based system performing a specific function such as mission planning or malfunction handling). These agents have the potential to function stand-alone but are also able to cooperate with other agents[14].

In a blackboard system, the agents are knowledge sources interacting through a shared memory: the blackboard[15]. Here, only knowledge is distributed, but data, information and control are central as compared to multi-agent systems. A common (shared) data structure for a complex crew assistant system with heterogeneous knowledge, data and functions is not likely to be obtained. A central blackboard system control will also be a bottleneck for real-time performance. Therefore the application of a blackboard system seems to be limited to single crew assistant functions only. In fact, the blackboard system concept provides a natural way to design and implement the layered, vertical, processing structure of a crew assistant function. Blackboard system technology can be suitable for specific crew assistant functions such as aircraft system status diagnosis[16], threat assessment[17], data fusion and object identification[18], and overall crew assistant system management[19].

4.3. Multi-agent system technology

While blackboard systems might be suitable at the crew assistant function level, multi-agent systems provide the technology and basis for the overall system architecture. This architecture will be based on multiple cooperative agents, where each agent implements a crew assistant function. Each agent has its own local data, information, knowledge, operations and control

that are relevant for the problem or task domain of the function. This encapsulation increases modularity and reduces complexity.

The agent capabilities and their potential to cooperate and achieve goals beyond the capabilities of a single agent determine the total system functionality. Cooperation in particular is the key to a sound crew assistant system architecture that is compliant with basic requirements such as modularity, reliability, real-time performance and comprehensible, predictable system behaviour. It directly addresses the key problem in the crew assistant as shown in the functional architecture: how to manage interaction between crew, crew assistant functions and aircraft systems, all being agents on their own. Important features for optimal cooperation and coordination in the crew assistant provided by multi-agent system technology are:

Organisation. A well-defined system organisation in order to oversee the complexity and to enhance real-time performance. A relatively fixed community-like organisation (following a set of rules of behaviour to avoid system conflicts or harmful behaviour) is preferred above a market-like organisation (which has dynamic negotiation as its key strategy and assumes well-defined task hierarchies that can be dynamically decomposed into nearly independent sub-tasks, which is unlikely to be the case with the crew assistant) or a centralised organisation (where a single coordinator will be a bottleneck).

Distribution. Knowledge, responsibilities, control and capabilities can be distributed and localised in crew assistant agents (through specialisation, dependency reduction, and increased local capabilities) so that coordination decisions are part of local decisions rather than a separate layer (coordinator) above local problem solving.

Planning. Planning (eg the plan-goal graph in the Pilot's Associate[19]) will synchronise individual agent's behaviour and will resolve conflicts before or during actual execution.

Contextual Awareness. Other methods to improve coordination are to develop and increase common contextual awareness between multi-agents so that they can make better and less conflicting decisions. A typical example is a function for situation assessment that maintains a world model that is accessible by all other functions. Coordination will be improved by a common awareness on what, how and when to communicate in which relevance, timeliness, and completeness of information are key properties[20]. Common knowledge will also avoid conflicts in the use of limited resources.

For reasons of modularity, real-time performance and reliability, it is argued that coordination and interface management not to be left to a single agent, but to distribute it and make it an integral part of each agent's cooperation capabilities. This means that in a multi-agent crew assistant system architecture, there is unlikely to be a central coordination and interface management as is present in the functional architecture.

Present state of the art DPS and multi-agent system technologies are expected to satisfy the requirements for a successful implementation of a crew assistant, especially in respect to: modularity, real-time performance, reliability, integration and system engineering[21]. Example crew assistant systems that already apply DPS technology are:

- ***Cockpit Information Management*** prototype system that uses a blackboard architecture as basis[22].
- ***Pilot's Associate*** which adopts a distributed blackboard architecture in order to structure the system as a heterogeneous, loosely coupled system in which individual agents are not restricted to a particular development environment or software approach[19]. Communication between modules was centrally coordinated by a blackboard-based agent called the Mission Manager, but this centralised approach has been abandoned in subsequent system design for complexity and performance reasons and is being decentralised and distributed among the agents.
- A ***prototype*** application[23] of an expert system that manages a set of cooperating expert systems. It provides interaction management towards the multiple expert systems as well as interaction management towards the crew, so that the complexity of the multi-expert system is hidden from the crew.
- ***Copilote Electronique*** which is based on a flexible heterogeneous implementation paradigm[3] which is evaluated on performance with the simulation tool SAHARA[24].

Maturity of multi-agent systems is reflected by a growing list of development tools which in most cases have integrated a blackboard system technology. For crew-assistant applications it is recommended that specific arrangements are made to ensure:

- a relatively fixed agent organisation in order to map each crew assistant function on a specific agent, to reduce control complexity and non-determinism (which guarantees a consistent and predictable behaviour towards the crew) and to provide predictable load balancing of the limited

computer resources in regard to data transfer bandwidth and processing power;
- a predictable conflict resolution where the agents opt for the same solutions (eg. selection of aircraft system modes) and the same use of resources (eg. choice of cockpit interfaces) to address consistently the limited cognitive capabilities of the crew.

5. CONCLUSIONS

A crew assistant is an on-board automated system which will support the crew in performing its task. It will enhance efficiency and flight safety in a demanding, complex operational environment. This is achieved by assigning (a part of) the crew task to the crew assistant. Depending on how much of the original task is delegated, the amount of information offered to the crew and the amount of control required of the crew will be significantly reduced. This will enable the crew to concentrate on essentials and make more effective decisions.

This paper presents a generic functional architecture of the crew assistant based on the operational environment in which it will operate. This functional architecture is modular in several dimensions and identifies:

- various separated crew assistant functional modules,
- different levels of data processing within each functional module,
- management modules which interface the crew assistant with crew and aircraft.

For crew assistant development, it is recommended to identify early in the design process the single or multiple functions supporting single or strongly related crew tasks. This will result in functional modules with a maximum of internal coherence and a minimum of interaction. Future modifications will also benefit from this modularity. When eg. a cockpit display has to be replaced, only the presentation module that addresses that display has to be adapted. The other modules remain unaffected.

The functional architecture includes various elements that are knowledge intensive. Advanced Information Processing provides technologies able to handle the complexity of the operational environment and to support sophisticated man-machine interaction.

This paper proposes Distributed Problem Solving technology in particular as a key technology to develop the functional architecture into a system architecture. The suggestion is to let a multi-agent system form the backbone of the architecture that includes coordination aspects and to apply blackboard system technology to local function-dependent problem solving. With respect to real-time operation, the multi-agent system architecture will be able to make a trade-off between agent communication and computation, and the agent's blackboard system is particularly suited to making problem-dependent trade-offs between quality and responsiveness.

Maturity of DPS development tools and existing realisations lead one to expect that next generation crew assistant applications will adopt widely the distributed problem solving and multi-agent technology. Specific arrangements are required to satisfy specific needs within a crew assistant application.

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Perspectives of Crew Assistance in Military Aircraft through Visualizing, Planning and Decision Aiding Functions

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1 SUMMARY

Due to increasing demands put on crews of military aircraft, effective cockpit systems will be required in order to reduce workload and to improve crew performance. This paper presents various approaches to crew assistance in tactical flight missions. The underlying tasks are tactical decision making, low-level flight planning and flight guidance. The integration of the Tactical Situation System as part of a knowledge based crew assistant and a flight guidance display system incorporating sensor and synthetic vision components offer a promising solution to improve the situational awareness of the crew. Respective prototypes have been successfully tested and evaluated in a simulated environment as well as by flight trials.

2 INTRODUCTION

2.1 Human factors in crew assistance

Human operators might be overtaxed due to the various tasks resulting from military air transport missions in hostile environments. Guiding the aircraft through adverse weather conditions in ground proximity puts further demands on crew performance. [5] Most accidents can be at least partly attributed to human erroneous actions due to increasing crew workload. [7] Human-centered automation [2] offers a promising approach to the solution of the obvious problems of the enabling technology oriented flight deck automation.

The main scope of present programmes on on-board pilot assistance is the enhancement of the crew's situational awareness. In order to improve the situation assessment capabilities it must be ensured that the attention of the cockpit crew is guided towards the objectively most urgent task of the situation and if necessary the workload is reduced to a normal degree which can be handled by the crew. [7] Under pressure of time the pilot's information processing performance might be shifted to a skill-based level. [9] Tasks, such as planning and decision making, performed on a rule/knowledge-based level under normal operating conditions can no longer be performed in situations with high workloads. Even different tasks yield specific pilot's strategies of information gathering and processing. [13, 15] Therefore, situation dependent assistance has to be provided in order to cover all aspects which are also to be considered as situational aspects by the cockpit crew. [7]

The next section deals with approaches of how to address human operators at different performance levels by using appropriate assisting functions.

2.2 Merging approaches for crew assistance

Various approaches for crew assistant systems emphasize different aspects concerning situations, resulting tasks, and respective human performance. The main scope of the activities is to merge the following approaches for crew assistance:

One approach to effective crew assistance in order to meet the requirements of human-centered design is to incorporate the capability of situation assessment. The situation assessment has to be perfomed by the cockpit crew continuously during flight. In parallel the same assessment is done by the functions of the machine part of the man-machine system. [7] The development of the Cockpit Assistant System CASSY and respective flight tests [8] covers this aspect in the field of civil air transport mission scenarios. In military environments additional aspects related to low-level flight planning and guidance and tactical constraints arise.

Another approach is to consider visual perception aspects of human performance in crew assistance. Enhanced and synthetic vision systems are the today's choice in order to improve the crew's situation awareness in the context of low-level flight guidance. While classical systems such as radar based terrain following systems or flight director systems avoid or at least decrease the involvement of the pilot, enhanced/synthetic vision systems keep the pilot active in the flight guidance loop. Thereby, the principles of the cognitive approach to flight deck automation can be met. [2, 15] Scientific research studies offer relevant design principles. [1, 3, 4, 10, 12, 17]

This paper presents a synthesis of the above two approaches to a *Tactical Situation System* representing the military operations related modules of the assistant system extended by the addition of an *Enhanced Flight Guidance System* to assist the pilot in manual visually guided flight at low altitudes and in adverse weather conditions.

3 KNOWLEDGE-BASED CREW ASSISTANCE

The Crew Assistant Military Aircraft (CAMA) is an on-board knowledge-based expert system for efficient crew assistance in military aircraft missions developed in cooperation with

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the University of the German Armed Forces Munich - which is responsible for the overall design [8, 16] - Deutsche Aerospace (DASA) and the German Aerospace Research Establishment (DLR). It is designed in a first stage to improve the situational awareness of the crew in air transport missions. Therefore, it assists the crew in planning and decision-making tasks through all flight phases.

The following two sections deal with general aspects of the CAMA system concept and the military operations related components.

3.1 Functional levels of the crew assistant

Figure 1 shows the core modules of the Crew Assistant Military Aircraft and its integration into the flight guidance loop. The electronic crew member gathers information from the crew via the monitoring of command and control actions. The aircraft and external data sources (ATC, Nav, weather etc.) are connected to the system by appropriate sensors or communication media.

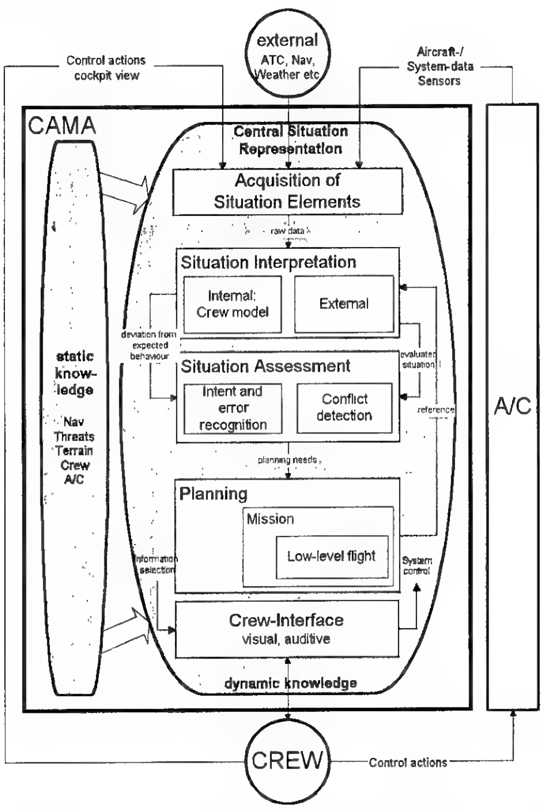

Figure 1: Crew Assistant Military Aircraft architecture

The *Central Situation Representation* is a dynamic object-oriented representation of situation relevant data. It contains all situation related (dynamic) and domain related (static) knowledge. The *Crew-Interface* is the audio-visual communication layer between the crew assistant and the crew. It selects and coordinates information to be shown on a 2D map display or issued via a speech synthesizer. The latter provides system control through speech recognition. The *Planning* layer generates a complete flight mission plan. [8] In the *Situation Interpretation* layer this flight plan is used as reference for the crew model. Here, the expected crew action patterns are elaborated and aspects of the external situation (tactical elements, terrain etc.) are evaluated. The modules in the *Situation Assessment* layer are supposed to detect conflicts in the expected succession of the flight and to recognize the crew's intents and errors. In the case of a pilot error, a warning or hint is given to the crew to correct the error. In order to cope with the temporary discrepancy of crew intent, CAMA tries to figure out the intention, modifies the flight plan accordingly, and elaborates the consistent expected behaviour again. [8] The structure of CAMA mirrors the general design philosophy not to allocate functions on the machine side or the crew side alone but to both sides in parallel. [7] Thus, assisting functions can be provided on all human performance levels.

3.2 Tactical situation related assistance

Deviations from the mission plan might be induced by the crew while reacting to a suddenly changing mission scenario. Therefore, the assistant system has to cope with the tactical situation in order to predict related crew behaviour patterns, recognize respective crew intents and errors and detect conflicts in mission plan execution. The Tactical Situation System as part of the crew assistance system consists of the following components:

- Tactical Situation Interpreter
- Low-altitude Flight Planner
- Tactical Situation Display
- Enhanced Flight Guidance Display

In order to incorporate tactical elements in the planning and decision-making considerations, the Tactical Situation Interpreter is integrated in the situation interpretation layer of CAMA. On the basis of a full-scale threat and terrain evaluation, a low-level flight plan is calculated by the Low-altitude Flight Planner. The Low-altitude Flight Planner is a submodule in the CAMA planning layer. The resulting low-level flight plan can be monitored according to the IFR (Instrument Flight Rules) flight plan supervision. A detailed flight trajectory is displayed to the pilot on the Enhanced Flight Guidance Display when assistance is needed on a skill-based level. The Tactical Situation Display offers a crew interface to the Tactical Situation System. It is an interactive map display depicting terrain elevation and cultural feature data, tactical and threat information as well as a variety of navigational elements.

The following chapter provides a closer view to the functions and architecture of the Tactical Situation System.

4 THE TACTICAL SITUATION SYSTEM

The Tactical Situation System [11] is a software prototype system developed in parallel to the CAMA activities. It covers the military operations related aspects of crew assistance in order to demonstrate advanced mission management technologies and support the pre-development phase of future air transport/weapon systems. The aim of the investigations is to create flexible system prototypes for cockpit avionics in order to elaborate user requirements and evaluate respective prototypes with operational personnel under human-machine-interaction considerations.

Based upon the experience gained in the development of the crew assistant the Tactical Situation System consists of four main modules as described as follows.

4.1 The Tactical Situation Interpreter

The Tactical Situation Interpreter is a knowledge-based module in the context of the situation interpretation layer as referring to the CAMA architecture. Its main contribution is the computation of a *threat map*. The calculation is based

upon digital terrain elevation data (DTED) [19] and the threat's models. Particular objects from a given list of tactical elements are regarded as threats such as surface-to-air missiles (SAM) or radar sites. A threat model contains the parameters

- maximum range,
- operationability,
- efficiency along range and
- respective models for threat area overlapping.

Figure 2 shows the principle steps of the algorithm for the threat value calculation.

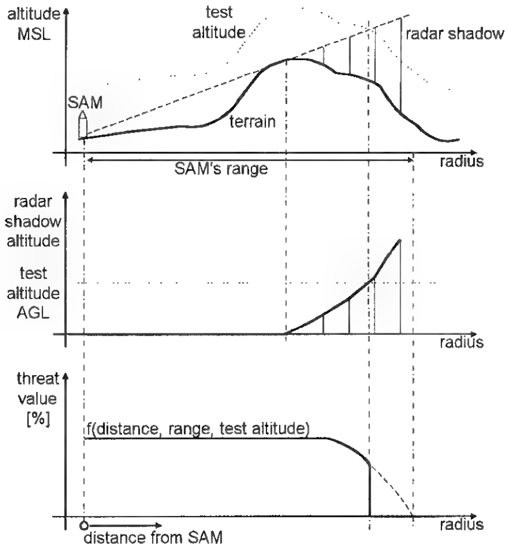

Figure 2: Threat map calculation

Due to the characteristics of the threat's radar systems and respective radar shadows resulting from the terrain structure, the altitude above ground up to which an aircraft is not detectable by the hostile radar beams can be derived from the digital terrain elevation database (DTED). Given a certain test altitude a threat value of zero can be assumed below these radar beams. Above the threat value is calculated as a function of the individual model parameter. The threat values are calculated for ten discrete altitudes above ground level (test altitudes every 50 meters in the z-axis) and for each terrain elevation grid point (longitude/latitude coordinates). Area overlapping of threats is taken into consideration by probability calculus.

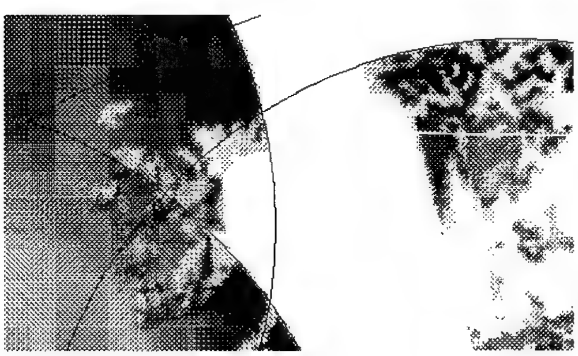

Figure 3: Threat map with SAMs' range circles

Figure 3 depicts a typical result of a threat map calculation. The actual threat is limited by the drawn range circle and by the radar shadow of a hill on the left.

4.2 The Low-altitude Flight Planner

The aim of the Low-altitude Flight Planner is the calculation of a three-dimensional route between mission-given waypoints with a maximum probability of survival in a hostile environment. This is achieved by avoiding threatened areas if possible, minimizing the exposure to unknown threats and keeping clear of the terrain. Therefore, the mission constraints, the tactical elements and the resulting threat map, the terrain elevation data and the aircraft performance data are taken into consideration. The output of the planner is a detailed trajectory and a waypoint/flightleg-oriented representation. Figure 4 shows the architecture concept of the planner.

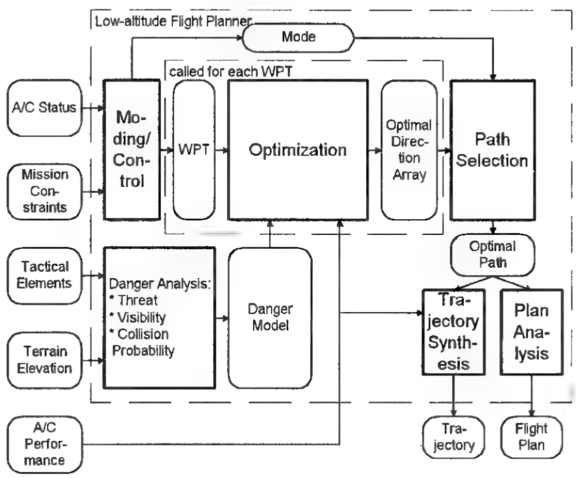

Figure 4: Low-altitude Flight Planner architecture

The system consists out of three functional submodules:

1. The *danger analysis* incorporates the threat map calculation as described in section 4.1. Additionally, the visibility at each point is calculated without assuming any particular threats. The algorithm issues lower danger values on the side of valleys than in the center. This behaviour reflects pilot's low-level flying preferences. Finally, the danger analysis utilizes the calculation of a ground collision probability, which is particularly high in rough terrain. This feature leads to generally higher flight altitudes in the absence of threats. An overall danger value is calculated for each terrain grid point and stored as a danger model in an array.
2. The *moding/control* checks the flight status and assembles the target point and the planning area for the *optimization* according to the mission constraints. The optimization provides an array of optimal directions to the target point. As long as a replanning does not imply a new target point another optimization run is not required. This means that the algorithm offers an optimal path from each point in the planning area to the desired target point. This calculation is done for each waypoint. The numerical optimization is based on dynamic programming [6] and uses a large number of calculation steps for global optimization. In order to achieve an operational system for in-flight replanning which provides a low-level flight plan in reasonable computing time, some heuristical

considerations have to be applied. The reduction of grid points to be taken into account is done by ignoring grid points beyond an ellipse around the actual flight leg.

3. The *path selection* depends on the current planning mode (initial planning or replanning). It constructs a terrain grid based flight path from a given start point, respectively present aircraft position to the target point. The *output assembly* functions *trajectory synthesis* and *plan analysis* form the Low-altitude Flight Planner output.

   - In order to be monitored by a pilot model based assistant system, the representation of the detailed trajectory has to be reduced to a waypoint based low altitude flight plan, which represents the general considerations to be followed in the human planning of low level missions i.e. threat avoidance, terrain masking, timing etc. The reduction is done through a low pass filtering operation of the optimal trajectory.
   - Additionally, the low-level flight plan is given by a detailed trajectory representation. Thereby, an assisting function on the skill-based human performance level can be provided. During normal operation the pilot selects the trajectory to fly by the consideration of relevant influences. The execution can be monitored by the crew assistant. In situations of increased workload it is possible that the pilot is no longer able to select a safe and efficient flight path. In this case the display of the automatically generated trajectory is a helpful tool.

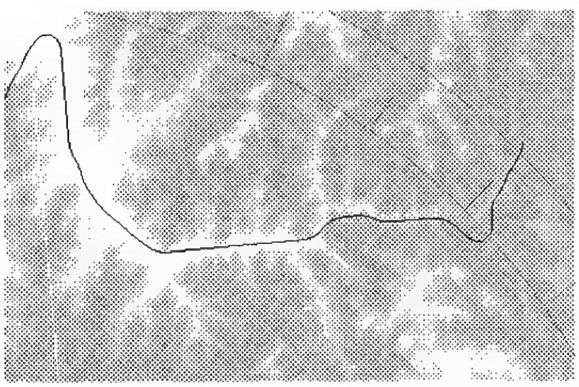

Figure 5: Low-altitude flight plan on elevation map

Figure 5 shows a typical planning result between two waypoints considering only the terrain elevation. The result is an optimal trajectory minimizing the cost function of weighted terrain elevation data and local threat values integrated over the complete flight path.

4.3 The Tactical Situation Display

The Tactical Situation Display provides the primary crew interface to the Tactical Situation System. Basically, it is an interactive electronic moving map display for navigational and operational purposes. The aim of the interface is the improvement of the pilot's situational awareness. Situational awareness is guaranteed if the pilot has all relevant information for the present flight situation at his disposal and is therefore able to cope with the posed tasks. The actual information needed for task performance is highly influenced by the task itself [13, 15]. Obviously, the map information required for radio navigation is completely different to the information in the context of visual navigation. Typically, the differences are more subtle. The Tactical Situation Display is primarily designed in order to cope with the advancing knowledge on human information processing. Therefore, it allows the composition of the display contents from a vector oriented database. The display utilizes digital terrain elevation data (DTED) and digital feature analysis data (DFAD) [19] in order to create a topographical map in any required scale and orientation (north/heading up). The various feature classes can be displayed selectively providing a very efficient decluttering of the screen contents. Radio navigation symbology can be added by visualizing Jeppesen Navigation Data. Military operations related aspects are covered by the incorporation of tactical symbols (as indicated in Figure 3). The threat map display can be activated for the different above ground levels or be slaved to the aircraft's present altitude. The ground track of the low-altitude flight plan is indicated as in Figure 5.

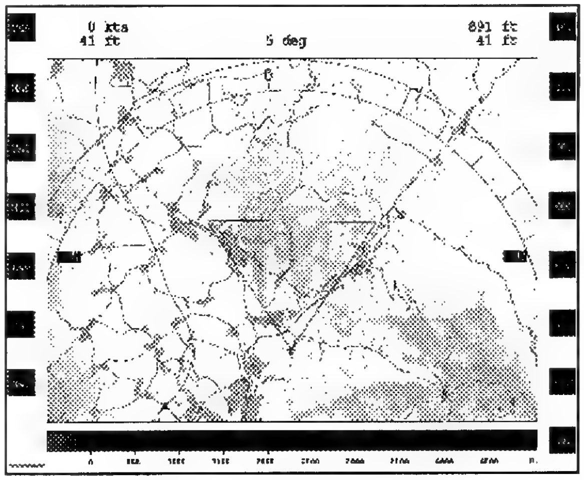

Figure 6: Tactical Situation Display

Figure 6 tries to give a general impression of the appearance of the Tactical Situation Display. It shows the display depicting the feature data and the threat map in a 1:100,000 heading-up representation. The system is designed as a head-down display.

Several other display elements are included in order to emphasize the correlation between the Tactical Situation Display and the Enhanced Flight Guidance Display (see section 4.4) with respect to human performance oriented system design. Details are given in section 4.5.

Additionally, the system provides an interface to the Low-altitude Flight Planner. It allows the pilot to enter waypoints interactively by marking them on the map. The control is done by use of a cockpit trackball for the analogue inputs and pushbuttons for the discrete inputs.

4.4 The Enhanced Flight Guidance Display

Several scientific research studies [3, 4, 10, 15] start from the assumption that the pilot's information gathering from the out-the-window view is critical for flight guidance in low-level flight and landing tasks. Flying under restricted visual conditions requires additional technical means to assist the pilot performing the task. Classical flight guidance systems for instrument flight, such as flight director display or ILS indicator, give only very reduced information gathered by simple sensors from the real-world situation. Therefore, the pilot's situational awareness might be fairly low and the pilot still has to learn adapted flying skills instead of just utilizing his natural and extremely powerful skills of flying in a three-dimensional visual world.

The Enhanced Flight Guidance Display is a promising approach to the solution of the problems with poor visibility low-level flight. It comprises an imaging sensor (e.g. FLIR, mmWR, LL-TV) and the superimposition of the sensor image with a computer-generated three-dimensional cockpit view. The incorporation of sensory data is essential for the benefit of the system. Due to incomplete or incorrect databases, the pilot cannot only rely on the synthetic image components. Inaccuracies of the navigation system yield another basic problem for just synthetic vision systems.

Thus, the Enanced Flight Guidance Display is not a synthetic vision system. It does not try to produce a most realistic representation of the out-the-window view as used in visual systems of training flight simulators but is instead a display carrying situation and task relevant information.

Therefore, the Enhanced Flight Guidance Display consists out of the following visual components:

- The *non-conformal flight guidance overlay* is a standard head-up display symbology with speed, altitude (MSL, AGL), heading, vertical velocity readouts and a bank and sideslip indicator.
- The *conformal flight guidance symbology* incorporates an attitude display and artificial horizon. The flight guidance tunnel visualizes the three-dimensional flight trajectory. A velocity vector and flight path predictor depict dynamic aircraft movement information. [18] The predictor symbol consists of three U-shaped brackets (for the 1, 2 and 3 second prediction) in order to fit into the flight guidance tunnel. The symbology is denoted as *tunnel dock* (see Figure 8, center).
- The *conformal terrain contour symbology* is a perspective depiction of the digital terrain elevation database. Air traffic obstacles exceeding a minimum height taken from the digital feature analysis database are shown as well as airfields.
- The *sensor image* is added to the synthetic parts of the display in order to cope with incomplete databases.

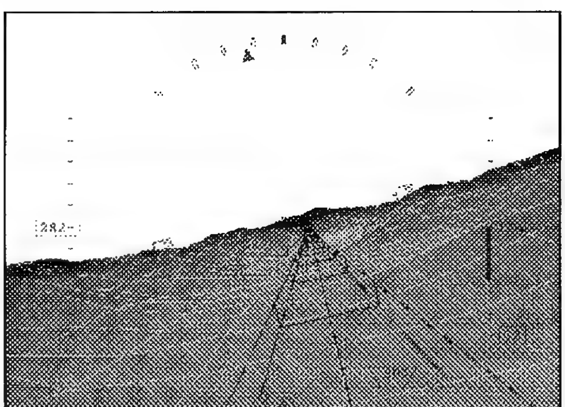

Figure 7: Synthetic symbology of Enhanced Flight Guidance Display

Figure 7 tries to depict the synthetic parts of the display. The format shown is typical for a head-down application, because of the coloured terrain surface. The colouring is switchable between:

- an absolute elevation coding colour key as used in the map display and
- a collision warning colour code, which assigns red colour to the terrain higher than the ownship altitude.

The same colour codes can be independently assigned to a perpendicular east/north-fixed terrain grid. Using only the terrain grid without the surface colouring produces a more head-up display type symbology which is applicable in combination with the sensor image (see Figure 8).

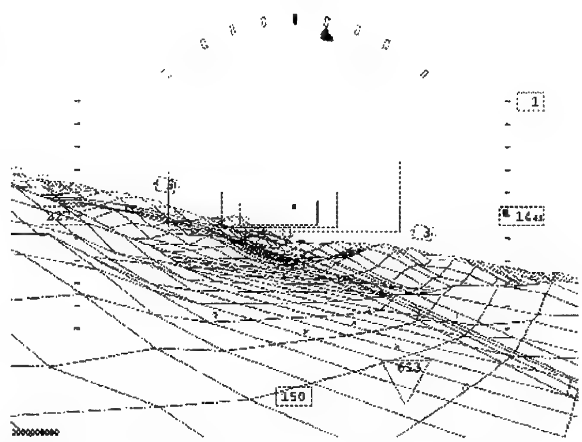

Figure 8: Flight guidance symbology for sensor image combination

The software prototype of the Enhanced Flight Guidance Display is designed in order to allow rapid changes of formats and functions to easily meet user and design requirements.

4.5 Correlation between 2D and 3D display

Due to the tasks arising out of the operational mission context, it can be expected that there will be a large workload connected with a 2D map display. This might lead to a loss of situational awareness concerning the aircraft's attitude and terrain proximity. Therefore, the concepts followed in the design of the Tactical Situation System try to enhance the correlation between the 2D map display and the 3D flight guidance display. The improvements should lead to:

- a better situational awareness concerning the aircraft's attitude while working with the 2D map. The pilot should be enabled to maintain the flight attitude even while working with the map for a longer time;
- an easier identification of visual objects in the map and the 3D representation for navigational purposes. The pilot should be assisted in finding and visually identifying navigational landmarks in either display and correlating them with the other representation. This implies that the integrated display system should clearly indicate the common displayed area;
- an intuitive understanding of the terrain contour. The pilot should be able to match the different representations of the terrain elevation without adding effort and therfore being aware of the surrounding terrain at any time. Thus, he can reduce the risk of dangerous terrain proximity even when concentrating on the map display;
- a sufficient awareness of the mission plan and flight path throughout the flight. The pilot should be enabled to correlate the overall mission plan and track information from the 2D display with the local flight guidance information give in the 3D display which leads to a better understanding of the temporary actions to be taken.

In order to achieve the desired improvements in the context of human-centered display design and effective crew

assistance, the following methods were applied and symbols were integrated in the displays.

- The map display is overlayed by a combined bank/flight path angle/pitch rate indicator on the periphery. Thereby, the pilot can gather information on attitude and attitude changes of the aircraft by means of peripheral vision while focussing on the central map for any task performance.
- The actual fields of view (and viewing distances) of the synthetic flight guidance overlay and the imaging sensor are propagated to the Tactical Situation Display and indicated by triangles. Thereby, the pilot can directly correlate locations on the map and in the perspective view.
- The colour coding of the conformal terrain contour symbology in the Enhanced Flight Guidance Display is identical to the map display. Thereby, the pilot can easily identify identical terrain relief elements such as ridgelines or valleys on both displays. The same principle is applicable for the terrain collision warning colouring in both displays. This feature allows the pilot to recognize terrain proximity by just regarding the map display.
- The generated low-altitude flight plan is transmitted to the map and flight guidance display in parallel.

5 EVALUATION CONCEPTS

In order to evaluate the approaches to crew assistance, particularly the Tactical Situation System, software prototypes are implemented and integrated in appropriate test environments. The tests are being done with respect to technical feasibility, human-machine-interaction considerations, and real-world conditions. Therefore, the Tactical Situation System and various subsystems are presently undergoing critical evaluation procedures which are described in the following sections broken down by method.

5.1 Functional demonstration and technical evaluation

The functional demonstration is the starting point of any technical evaluation. Therefore, the subsystems of the Tactical Situation System were implmented on Silicon Graphics UNIX Workstations using the C programming language. Particularly the Enhanced Flight Guidance Display requires additional effort in order to develop display formats and appropriate symbology. Presently, a development tool is being built which allows the combination of the synthetic parts of the display with a recording of a sensor image.

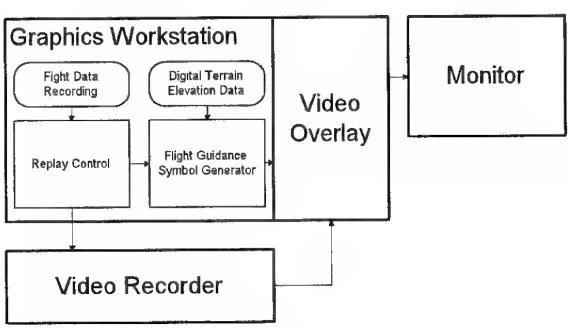

Figure 9: Sensor image recording dynamically combined with synthetic symbology

Figure 9 shows the structure of the replay system. The approach utilizes pre-recorded sensor images with related flight data recordings from flight trials. The replay control feeds the flight data into the Flight Guidance Symbol Generator while starting the video player synchronously. The video overlay is either done digitally with appropiate hardware in the graphics workstation or optically on a projection screen using two projectors. Thereby, a dynamic image can be produced in a laboratory environment which is very close to the real-world appearance.

5.2 Human-machine-interaction evaluation

In order to evaluate the system under human-machine-interaction aspects, the prototypes have been integrated in a flight simulation environment. The required elements are:

- The *dynamic simulation* calculates the aircraft movements and models the subsystems' behaviour according to the pilot's control actions.
- The *cockpit simulation* is the human-machine-interface to the avionics systems prototypes and is designed as a tool for any human performance/behaviour and acceptance studies. The cockpit is designed as a glass-cockpit with a generic layout in order to be easily adapted to different configurations. Figure 10 shows the layout of the display areas and the controls including Primary Flight Displays (PFD), a Radio Management Unit (RMU) running on a Control and Display Unit (CDU) with touchscreen control, a Flight Control Unit (FCU), a sidestick, throttle, and application monitors.
- The *visual simulation* is supposed to be supporting the activities concerning Enhanced Flight Guidance Display. The visual simulation will be built by use of a projection system (see Figure 10).
- The *application software interface* allows the integration of avionics software prototypes in order to evaluate the functions in an interactive dynamic flight simulation environment. Thereby, it is possible for cockpit crews to directly interact with the systems to be tested.

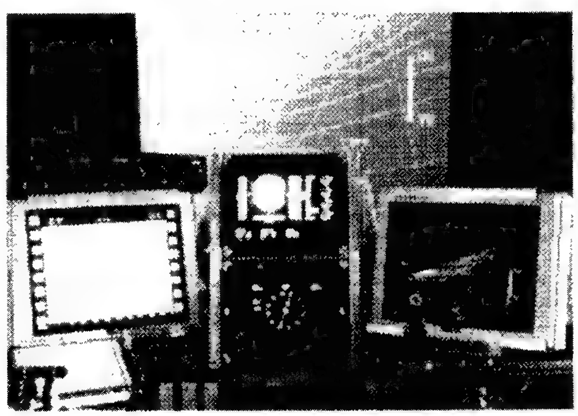

Figure 10: Cockpit layout

In order to offer an opportunity to evaluate the Enhanced Flight Guidance Display in the simulation environment with operational flight crews, an interactive sensor image simulation is presently beeing built. It is based upon sensor characteristics models and digital terrain elevation and feature data.

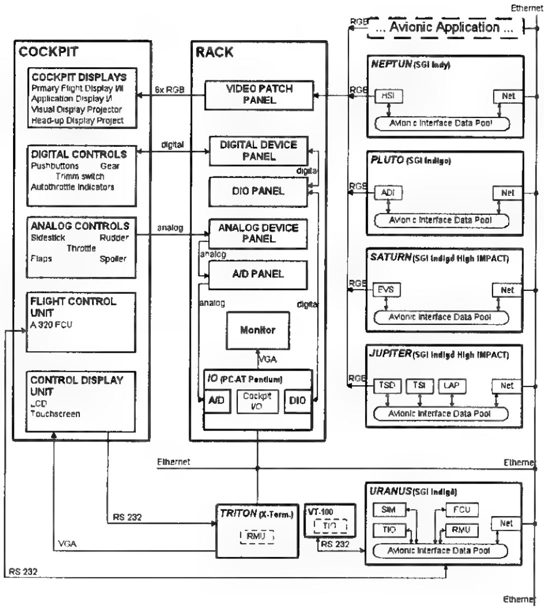

Figure 11: Hard- and software architecture of the Avionics System Demonstrator, ASD

Figure 11 shows the open hard- and software architecture of the flight simulation system (Avionics System Demonstrator, ASD). Due to the availability of the entire situation relevant data (held in the Avionic Interface Data Pool) on each integrated computer system, other prototype systems can be integrated easily and hardware-in-the-loop testing facilities can be provided.

5.3 Field trials and results

Several flight trials concerning the evaluation of Enhanced Flight Guidance Display formats have been conducted recently.

The following overview [11, 14] provides some details concerning the recent experimental activities:

- Experiment 1:
  Time: December '94
  Terrain structure: river valley
  Plattform: Do 128
  Terrain grid: no
  FLIR: video image based simulation
  Obstacle cueing: yes
  Display HW: helmet-mounted display
  Objectives: principal operationability
  Subjects: 1 test pilot
  Task: low-level terrain masking
  Result: HW/SW operational in test aircraft, pilot is able to stay in tunnel and follow river valley
  Project partner: TU Munich, TU Braunschweig
- Experiment 2:
  Time: August '95
  Terrain structure: deep mountain valleys
  Plattform: Do 128
  Terrain grid: yes
  FLIR: video image based simulation
  Obstacle cueing: yes
  Display HW: helmet-mounted display
  Objectives: technical operationability
  Subjects: 1 test pilot
  Task: missed approach procedures
  Result: slight problems with hardware, pilot is able to follow the tunnel
  Project partner: TU Munich, TU Braunschweig
- Experiment 3:
  Time: October '95
  Terrain structure: hilly terrain
  Plattform: A 320 simulator
  Terrain grid: no
  FLIR: synthetic digital data based image
  Obstacle cueing: yes
  Display HW: head-up display
  Objectives: pilot acceptance
  Subjects: 6 military transport pilots
  Task: low-level (150 ft) terrain masking
  Result: system is well accepted by pilots as a positive assisting function, obstacle cueing useful
  Project partner: DASA
- Experiment 4:
  Time: March '96
  Terrain structure: hilly terrain
  Plattform: Do 128
  Terrain grid: yes
  FLIR: video image based simulation
  Obstacle cueing: yes
  Display HW: helmet-mounted display
  Objectives: pilot performance
  Subjects: 1 test pilot
  Task: low-level terrain masking
  Result: pilot uttered great confidence in the system, flight could be successfully conducted under real low visibility conditions
  Project partner: TU Munich, TU Braunschweig

The first two experiments were conducted in order to elaborate the configuration of the aircraft equipment and to demonstrate the principle functional operability of the system. Several enhanced vision guided flights through a river valley in southern Germany and standard missed approach routes from an airport in a mountain valley could be successfully completed. The simulator experiments provided some preliminary results with respect to pilot acceptance in a low-level flight task. The latest flight tests aimed to reproduce the simulator flight tasks and respective mission plan in real flight. The objective was the measurement of the pilot's performance.

6 CONCLUSIONS

The aim of the presented research and development activities is to provide advanced cockpit avionics systems improving the crew's situational awareness with respect to a safe and successful mission completion. This is done by use of technical means such as knowledge-based on-board systems in the context of human-centered cockpit automation. The Crew Assistant Military Aircraft (CAMA) yields a promising approach to assistance in planning and decision-making tasks. The Tactical Situation System extracts the military operations related subsystems which are the Tactical Situation Interpreter, the Low-altitude Flight Planner, and the Tactical Situation Display. The system is enlarged by the

Enhanced Flight Guidance Display which offers visual flight guidance information to the crew for poor visibility low-level flight operations. Thereby, crew assistance can be provided on each human performance level including highly cognitive planning tasks as well as sensomotoric flight control tasks. A major aspect of the prototype development is the intgration of the different modules in order to achieve an efficient assistant system. Therefore, the interaction between the 2D Tactical Situation Display and the 3D Enhanced Flight Guidance Display is emphasized from an information presentation point of view.

In order to evaluate the system under technical and human-machine-interaction aspects, software prototypes are being developed and integrated in a flight simulation environment. The Enhanced Flight Guidance Display has already been successfully tested in several flight trials. The results show that this approach to visual flight guidance assistance is extremely powerful and yields a high potential for further developments in the field of human-centered cockpit design.

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Sensor Fusion for Modern Fighter Aircraft

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1 SUMMARY

Sensor Fusion has become important for fighter aircraft in order to improve the air picture with respect to the displayed area of all sensors, the precision of target's kinematic data, the confidence in the target's identity, and to support the management of the sensors. The paper investigates system architectures of existing and future sensors. Based on a Bayesian fusion approach, the benefits and constrains of data throughput, accuracy and track consistency is shown. The results of simulation runs with radar, IR and ESM sensor models together with a data link network are presented.

2 KEYWORDS

Sensor Fusion, Data Fusion, Multisensor Data Fusion, Track-to-Track Correlation, Centralised Data Fusion

3 INTRODUCTION

Existing fighter aircraft present their sensor information on separate displays or indicators to the pilots, and the aircrew must fuse and evaluate the information. With increasing complexity of the scenarios, more onboard sensors, the capability of the sensors to process more targets, and the multirole capability of modern fighters, the requirements for pilot support functions to evaluate all this multisensor data has become essential. Additionally the bandwidth of data link networks has been increased and allows the exchange of near real-time kinematic and identity data among fighters, AEWs and C2 units. New aircraft developments, like the European EF 2000, the American F-22, as well as combat improvements of existing aircraft will have Sensor or Data Fusion facilities.

In the past 20 years Sensor Fusion has been thoroughly investigated and numerous literature is available [e.g. 1, 2, 3]. The Joint Directors of Laboratories Data Fusion Subpanel, a DoD US Government panel, has defined a functional description with different levels. The first level defines the combination of kinematic and identity data, the second the situation assessment, the third the threat assessment, and the fourth which is often part of the first level optimises the management of the sensors in order to improve the kinematic and identity data.

It is obvious that only parts of this general description for Sensor Fusion can be used for fighter aircraft. The Level 1 taxonomy is well established and numerous publications are available, whereas Level 2 to 4 are not properly defined and visualise the different aspects to be considered.

This paper describes architectures for Sensor Fusion in a fighter aircraft, based on the capabilities and constrains of the sensors which are available or under development. It investigates solutions for Level 1 and Level 4 functions and their impacts on the process load and the data accuracy. Level 2 and 3 aspects are not considered.

4 OPERATIONAL BACKGROUND

The primary role of a fighter aircraft is the air-to-air mission which comprises the air defence and the offensive bomber escort role. As a secondary role different air-to-ground missions must be considered. In addition with the availability of powerful data link networks, another role, the contribution of kinematic and identity target data by the fighter aircraft to the air picture of the network becomes important.

An important number is the amount of tracks which have to maintained onboard the fighter aircraft. The literature refers to 10 to 30 tracks to be relevant for a mission [1]. If however a complete air picture for a mission area must be observed, the number of tracks can exceed 200.

In its primary role the fighter has to gain a superior position to win the air fight against hostile fighter aircraft, usually together with co-operating fighters. Additionally, low flying bombers must be intercepted in the air defence role.

In these situations fighters have the problem that the air picture provided from a single sensor, the own radar, is insufficient with respect to the observed space, the identity and the number of the tracks. In the beyond visual range attack, launched missiles must be supported with track data, as accurate as possible to improve the probability of intercept. Therefore the tracks against which the missiles are fired require a higher update rate with the consequence that other tracks may be lost or become inaccurate.

In the secondary role the problem of an insufficient air picture from above is amplified, because the fighter is flying at lower levels, and a single sensor must be utilised for the target acquisition or as flying aid.

The problems mentioned above cannot be totally resolved due to the stochastic characteristics of a scenario.

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Any air or ground track has a certain uncertainty, may be at the wrong position, or may have an incorrect identity. A certain probability exists that a real target is never detected or a track in the air picture is a ghost.

With Sensor Fusion the synergy of the different sensors can be used to minimise these problems. If the whole spectrum from IR to radio frequencies is observed, the detection probability is increased and the vulnerability to hostile deception techniques is decreased. If several sensors provide data about the same target, the quality of the kinematic data is improved and confidence in the identity is augmented. The space to be observed can be split in different sensor regions whereby one sensor can be supported by another sensor provided his kinematic or identity data are insufficient.

5 SENSORS

Sensor Fusion is determined by the quality of the data provided by the onboard sensors and the external data from the data link network. The crucial aspects are the accuracy and the latency of the kinematic data, e.g. range, range rate and angles, the search volume of the sensors, and the confidence in the identity declarations.

5.1 Multi Mode Fighter Radar

The advantages of a multi mode radar with a frequency range from 8 GHz to 12 (20) GHz compared with other sensors are its insensitivity with respect to the environmental conditions, its possibility to measure the range and the range rate additionally to the angles, at least in a benign environment, and its possibility to discriminate air or ground targets from the background clutter. Additionally the radar provides non-cooperative identification facilities by the so-called Jet Engine Modulation (JEM) and High Precision Ranging (HPR).

The disadvantages are its radiation which allow other sites the detection and identification at long distances, and the limited search volume. In a hostile environment the range and range rate is difficult to achieve and there is a competition between hostile jamming techniques and the anti-jamming capability of the radar.

The accuracy of the radar data highly depend on the number of tracks it must maintain. If 20 tracks must be maintained, a search volume of 100 deg $\times$ 6 deg $\times$ 100 km with 4 s frame time is typical. Then the track accuracy for the delivery of beyond visaul range missiles against highly manoeuvring targets is insufficient. The probability that the tracks are lost is high, and the targets may fly out of the search volume too fast. The same effect may occur, if low flying bombers and high flying fighters must be simultaneously tracked. For a head-on scenario the detection range is too short to establish confirmed tracks, identify the targets, and to perform the target assignments in co-operation with other fighters or a C2 unit.

These problems may be partially resolved by new developments in the radar technology, like adaptive sampling, better manoeuvre modelling in the tracker, or improvements of the signal processing. But the physical constrains of the antenna diameter, the available power and the signal-to-noise ratio will always define one boundary condition and the required time on target for non-cooperative identification and precise Doppler measurements the other.

With 50 ms to 100 ms time on target, 20 tracks require 1 s to 2.5 s frame time with adaptive sampling. If 2 s are used for the search of new targets, a frame time of approximately 4 s results with the problems described above. Therefore, the time between two target updates must be shortened. But if 10 to 30 relevant tracks have to be maintained onboard the fighter, other sensors must be used to support the radar.

5.2 Missile Radar

If the fighter is equipped with missiles which have a radar seeker head the missiles can contribute target data in their lock follow mode with a high update rate. Such a design is limited by the detection range and the aperture of the missile radars. If a missile radar is capable to track a target beyond visaul range no post launch support would be required and the missile could be used as a fire and forget weapon. Usually the missile radar has not this capability and needs a post launch support. Therefore, only targets considerably inside a range where a successful missile launch is possible can be tracked. But these tracks should represent the less important targets.

5.3 Optical Sensor

The spectral region from 0.4 µm to 14 µm offers four detection windows, one in the visible and three in the IR region. Sensors operating in the visible spectrum are limited by weather conditions. The benefits of the better angular resolution compared with the IR region cannot compensate these constrains. Therefore only the search and tracking function of an IR sensor, an IRST, is feasible for fighter aircraft.

The advantages of an IRST are its passive mode of operation and, compared with the radar, its theoretical better angular resolution. The disadvantages are the sensitivity of the detection range with respect to weather conditions, and the impossibility to measure range and range rate. The IRST tracker based on angular measurements only needs therefore more time to provide an appropriate target position than a radar which measures additionally the range and range rate.

The advantage of the passive mode of operation is on the other hand a disadvantage, because the IRST cannot support a beyond visaul range missile after launch. As the radar is the primary sensor of a fighter aircraft, installation problems exist, which cause obscuration effects with respect to the vertical or horizontal plane. Compared with the detection range, the identification capability from image analysis is poor due to the diffraction criteria. Classification of targets may be achieved at sufficient distances if all three IR windows are examined, which requires two separate detector arrays.

These problems cannot be resolved within a single IRST. Even by using a LASER for the the slant range

measurement the detection range would be too poor compared with a radar.

But in conjunction with other sensors these disadvantages can be be avoided. Another sensor can prime the IRST with range and range rate information, for the track initialisation. With this initialisation data the IRST can track a target for a sufficient time. The fighter radar and the IRST can co-operatively track the relevant targets, by splitting the search volume and dividing the frame time in halve. With a more sophisticated sensor management the reduction of the track update time can be achieved if both sensors observe the same volume.

5.4 Missile with IR Seeker Head

Missiles with IR seeker heads may be used in the same way as missiles with a radar seeker head. But the missiles with an IR sensor can provide data with the same accuracy as the onboard sensor, the IRST, because the aperture and the signal to noise ratio defining factors are comparable.

Therefore measurements or track data from IR missiles are candidates for Sensor Fusion in a fighter aircraft. If the IR seeker head is primed with target data from another sensor, it can continuously provide target data with good angular accuracies.

5.5 IFF Interrogator

The advantage of an IFF interrogator is the detection range due to the co-operative measurement. The range resolution is sufficient as well as the angular resolution of a monopuls IFF. Together with a Mode 3/C response a sufficient three dimensional location can be achieved. The crypto Mode 4 provides a good anti spoofing capability. The Mode 1, 2 or 3/A can be used for tracking purposes to distinguish different co-operating tracks from each other. The disadvantage of an IFF is that it is designed to operate in conjunction with 2D surveillance radars. Therefore it provides only an azimuth angle. For fighters whose radar/IFF antenna has no roll compensation this causes significant problems, because the precise azimuth now depends on the aircraft manoeuvres.

The use of the IFF interrogator depends on the operational constrains. If it is used in a continuous mode, it permanently emits interrogations in the search volume. The received responses, together with the radar measurements, can be used to update the tracks. If the IFF interrogator is used for identification purposes only, the continuous interrogation of the whole space is superfluous. In this case only unknown tracks from other sensors are interrogated. In both cases Sensor Fusion is required, because the IFF responses must be associated with other tracks, the kinematic data may be used to update the target positions, and the received responses are used to identify the targets.

5.6 ESM/LW/MAW

The ESM, LW and MAW are warning sensors aboard a fighter aircraft. The advantage of an ESM is its detection range and all three sensors can detect emissions from any direction. The ESM can identify hostile target types if they are contained in its emitter library. The disadvantage of all warning sensors are their inaccurate angular target data and that the target range can only be derived from the emitter library.

Therefore it is difficult to associate identity data from ESM, LW or MAW sensors with tracks from other sensors in a dense scenario. Solutions for this problem are the use of the more precise identity information of the sensors for the the association. But this requires that the track to which the ESM identity information is assigned to, e.g. a radar track, must contain identity data. Another solution makes use of the statistical independence of kinematic track data from a radar or an IRST and the ESM angles [4]. The normalised distances can subsequently summed up, the uncertainties decease and wrong correlation pairs will be sorted out by their increasing biases. This requires that ESM does not confuse the angles of arrival of the radiating targets and track these targets by their identity data.

5.7 Data Link Network

Within a data link network the exchange of target kinematic and identity data is possible. Network participants can provide their own position, their target tracks, or their sensor measurements. Compared with the onboard sensors the problem of a common co-ordinate system, and a common time becomes more severe.

The applicability of these data depends on the physical link and the bandwidth of the network. The physical link must assure that the messages can be received by the addressee and the message cannot be encoded or jammed by a hostile site. The bandwidth must assure that all data are exchanged with a minimum latency.

Within a mission area controlled by a C2 unit, three types of data sources can be distinguished. The C2 unit provides its air picture, network participants a self identification, and if they have own sensors, their sensor data can be transmitted.

The C2 unit provides its own air picture from its C2 radar, from an AEW aircraft or from neighbour C2 units. The tracks may exceed the above mentioned 200, but the accuracy of the kinematic data may be low due to the update rates and the measurement characteristics of the C2 radars. The subsequent changes of the co-ordinate systems require numerous data for a complete description of the track uncertainties. Actual systems have not the capability to provide these parameters and, due to historical reasons, use simplified descriptions like a Circular Error Probability (CEP). This generates additional uncertainties and biases. The identity of the C2 tracks is usually more confident than the track identity of a single site, because a C2 unit has access to more identity information.

Network participants like other fighters provide their own kinematic data for self identification purposes. The accuracy should be high, and if the fighter has a GPS in its navigation system, the uncertainties can be described by a CEP.

Any non-C2 unit with onboard sensors like radar, IRST, IFF or ESM can contribute its kinematic and identity target data. For the description of the uncertainties there exist a similar problem as for the C2 unit. Another aspect is whether raw data like kinematic measurement or identity declarations, or filtered data like tracks and identity likelihood vectors should be transmitted. The different aspects are discussed in Chapter 5.

It is easy to implement a unique definition of the tracks from the C2 unit and the self identification data of the network participants by appropriate identifiers within the network. For their combination no Sensor Fusion is required. Tracks or measurements from non-C2 sites are not unique and messages from different sites may describe the same target. A Sensor Fusion for the unification of the messages is therefore required for which different design alternatives are possible.

A hierarchy design associates the tracks at a central node, the C2 unit. The non-C2 sites receive only uniquely identified track data from other sites, the other messages are ignored. Such a design requires Sensor Fusion only for the C2 unit, but it is inflexible with respect to time constrains and the data exchange without a C2 unit.

A distributed design allows each network participant to associate and fuse the received data at their own platform, together with the onboard sensor data. Different results may may occur at each fusion node, and strategies for their resolution must be designed.

6 DESIGN PRINCIPLES

6.1 Architecture Alternatives

The design of Sensor Fusion systems is highly dependent on the sensor hardware. Sensors, responsible for the estimation of the target kinematics, like the radar or IRST, have a tracking system and provide only track data but no measurements. Other sensors without a tracker like the IFF or the ESM can supply only their measurements.

Two main design principles and numerous mixtures are are published [3,5]:

1.) A sensor level architecture combines the tracks of the individual sensors,

2) a centralised architecture where all the sensor measurements are fed to a central tracker, and

3) combined architectures which utilise measurements and track data, dependent on the situation, or exchange the results between the sensors and fusion nodes.

6.1.1 Sensor-Level or Autonomous Architecture

The autonomous or sensor-level architecture has a tracking system in each sensor. The sensors provide their tracks to a central fusion node which associates the data by a track-to-track correlation. Data which belong to the same target may be merged in order to improve the kinematic data, or it is simply indicated which sensor track represents the same target, in order to declutter the air picture.

The advantage of such an architecture is that existing sensors can be used. Only minor modifications are required, because the track data, provided from most sensors, do not contain all the accuracy and tracker data required for the association and fusion. But all these data are available within the sensors. The data transfer is not significantly increased, because the track update time is typically between 1 s and 5 s and no measurements must be transmitted via the bus. All individual sensors maintain their own tracks which guarantees a high redundancy. If one sensor becomes degraded, tracks of the other sensors are not affected.

The disadvantage of the sensor-level architecture compared with the centralised architecture, is the lower accuracy of the fused tracks. The continuity of the fused track compared with the sensor tracks cannot be significantly improved. As a result, tracks which are lost or confused by a single sensor due to its low update rate and/or target manoeuvres, are often lost at the fusion node of the central unit. The correlation and fusion algorithms are complex due to the statistical dependencies of the tracks.

6.1.2 Centralized Architecture

For the centralised architecture the measurements of each individual sensor are fed to the central fusion node, where the measurement-to track association and the tracking of the targets is performed. This approach provides the best accuracies of all architectures [6]. As a consequence the missassociation is less severe than for the sensor level arcitecture. The association and the track update equations are simple, due to the statistical independence of sensor measurements and tracks. Compared with a single sensor track, the continuity of the central track is better and it is faster converged, because the update rate is increased.

The disadvantage of a centralised architecture is the high data transfer load on the data bus due to the clutter, false alarms etc. received in the sensors. As a result of this high amount of data the processing load for the association will also increase and the track initialisation and deletion are more complex. The architecture is more vulnerable to degraded sensor data, and the redundancy is a problem, because the whole air picture is lost, if the central fusion node fails. Due to the amount of measurements from the different sensors the processing load for the association may become too high.

6.1.3 Combined Architectures

Numerous other approaches exist to overcome the problems of the first two approaches, without loosing their benefits.

One alternative is the implementation of both, a track-to-track and a measurement-to-track correlation and fusion at the central fusion node. To avoid track initialisa-

tion problems the sensor level track files are used to initiate or delete the central tracks. If more accurate track data is required, the central fusion node is switched from the track-to-track to measurement-to-track correlation. The sensor level track files can be used to reduce the data bus load, if only measurements which have updated the sensor level tracks are fed to the central track.

Another alternative is the feed back of information between the central fusion node and the sensors. The sensors provide their tracks to the central fusion node which performs a track-to-track correlation and fusion. The results of the fusion, the state vectors of the tracks and their covariances, are periodically send back to the sensors in order to improve the sensor level tracks. This improves the continuity and accuracy of the sensor level tracks, particularly for sensors which utilise angle only measurements for their trackers. The approach is applicable for both a data link network and within a fighter aircraft, because the maximum data transfer load is predetermined by the number of tracks and the time intervals between the messages from one network participant to another, or from the sensors to the central fusion node and vice versa.

6.2 Processing Functions

The taxonomy for the processing of kinematic data is well established in the literature. Most of the functions can be compared with the processing of a single sensor. The steps are (1) the alignment of the data with respect to the time and the co-ordinate system, (2) the gating and the calculation of a suitable distance measure between the tracks or the measurements and the tracks, (3) a formation of clusters to form group tracks and to support the identification, (4) the assignment of measurements or sensor tracks to a central track, and (5) the fusion of the identity and the kinematic data of the sensor reports.

6.2.1 Alignment

For a single sensor, like a radar, the time alignment is the prediction of the track state vectors and their covariance matrices from the last track update time to the time of new measurements. The co-ordinates of the measurements and their uncertainties are transformed to the co-ordinate system of the tracks.

The same process is required for the centralised architecture, to perform the measurement-to-track association in the central fusion node. Different co-ordinate transformations may be required to account for the characteristics of each individual sensor.

In the sensor level architecture the central fusion node or the sensors themselves can perform the time and the co-ordinate alignment. For the onboard sensors a spherical geodetic (North, East, Down) co-ordinate system is suitable. For sensors which provide their track data in this co-ordinate system no co-ordinate transformation is required and the time alignment can be simplified. Often a time alignment may be omitted, because the effect of the extrapolation is negligible compared with the sensor accuracies, e.g. for a radar-ESM correlation.

The transformation of tracks from the data link network requires more effort, because the tracks must be transformed from a co-ordinate system, suitable for all network participants, e.g. a Word Geodetic System (WGS 84), to an onboard system. If the track's uncertainty is described by a single CEP, some effort is required to reconstruct a suitable uncertainty description. If a covariance matrix or an error ellipse is available it must be transformed to the onboard co-ordinate system.

6.2.2 Gating and Distance Measure

The gating is used to determine the measurements or tracks of the sensors which belong to the same target. Usually rectangular and/or elliptical gates are used for this purpose.

Equation (1) shows an example for the rectangular gate of the range estimates from different sensors.

$$|\hat{r}_1(t) - \hat{r}_2(t)| \le const. \sqrt{\sigma_{1,r}^2 + \sigma_{2,r}^2} \qquad (1)$$

The gate size is defined by the uncertainties of the measurements and the tracks or by the uncertainties of the two tracks. If the difference of the state vector components is less than the gate size, the two tracks are subjected to further association processing.

The rectangular gates are cheap to implement from the processing power point of view, and if their hierarchy is well designed most of the unlikely combinations may be sorted out after the first gate.

If several candidates belong to the same rectangular gate an appropriate distance measure must be calculated. For measurement to track association the normalised distances together with their residuals, known from Kalman filter, are applicable.

Equation (2) describes the normalised distance, d, for two tracks with the state vectors $\hat{x}_1(t)$ and $\hat{x}_2(t)$:

$$[\hat{x}_1(t) - \hat{x}_2(t)]^T S^{-1} [\hat{x}_1(t) - \hat{x}_2(t)] = d^2 \qquad (2)$$

with:

$$S = P_1 + P_2 - P_{12} - P_{12}^T$$

Due to the common manoeuvre noise the cross covariance matrix P_{12} must be considered in addition to the track covariance matrices P_1 and P_2 of the single sensors. P_{12} depends on the filter gains, the manoeuvre models and the measurement matrices of the sensor and P_{12} from the the previous normalised distance [7]. They are therefore difficult to evaluate because these data are usually neither provided from the onboard sensors nor from a data link network.

6.2.3 Clustering

Usually the distance measure is used to perform the final assignment of the tracks or measurement. But, in a dense scenario, with 200 tracks, the assignment matrix may become too large. Additionally, the assignment is a probabilistic process which selects the most likely track pair. If there are several candidates the probability that the solution is correct is often poor, because the probability of other track pairs may be comparable. This may occur for a radar-ESM association. Assuming a Nearest Neighbour (NN) algorithm would be applied for the association of many tracks with good identities, but kinematic data with large variances, an identification conflict would possibly occur, because the kinematic correlation would not assign the tracks correctly.

Clustering is a measure to overcome these problems. By the clustering large assignment matrices can be partitioned into smaller ones. Unique track pairs can be sorted out. Clusters with several tracks, but the same identity, may form a group track.

6.2.4 Assigment

The assignment is known from the NN approach of a single sensor, where a measurement is used for the update of its nearest track only, instead of a probabilistic approach were measurements can update all tracks to which they may belong.

For the track-to-track correlation a NN approach is appropriate. The distance measures, derived in the association, are the elements of the assignment matrix. The number of sensor tracks which belong to the same cluster define its dimension. Numerous optimal and suboptimal approaches are known. The Munkres algorithm [8] is a favourite of the optimal assignments. Unfortunately the processing load increases with an exponent between two and three if the number of tracks, which belong to the same cluster, increase. Therefore a suboptimal assignment algorithm, which increase with an exponent of two, is sufficient, if only a display declutter is required.

6.2.5 Fusion

The centralised architecture requires a fusion algorithm, e.g. a Kalman filter at the central fusion node. For the sensor level achitectures one representative sensor level track is often sufficient to describe the target kinematics. Only if the accuracy of a track is insufficient, or if the estimates of the central fusion node are used to prime the sensor level trackers a fusion is appropriate.

For the standard Kalman filter form, Equation (3) describes the fusion of two updated sensor state vectors at time t:

$$\hat{x}(t) = \hat{x}_1(t) + [P_1 - P_{12}]S^{-1}[\hat{x}_2(t) - \hat{x}_2(t)] \qquad (3)$$

where P_1 and P_2 are the covariance matrices of the sensors and P_{12} is the cross covariance matrix between the sensor state vectors, and S the residual, as defined in Equation (2).

The covariance matrix P of the fused estimate is given by Equation (4):

$$P = P_1 - [P_1 - P_{12}]S^{-1}[P_1 - P_{12}]^T \qquad (4)$$

7 RESULTS

Experiments have been carried out to evaluate the performance of a sensor level architecture for a fighter aircraft equipped with a radar, an IRST and an ESM. Additionally the fighter receives link data from a C2 unit, self identification data from network participants and sensor data from the network participants.

The hardware environment for the performance evaluation consists of a VAX computer for the simulation of the aircraft model and the sensors, and a commercial VME board equipped with a Motorola 68020/68882 processor as target hardware for the Sensor Fusion.

Two examples are shown, the first describes the processing for two sensors, each providing 20 tracks, which is an example for the correlation of onboard sensors. The second depicts a situation of 200 by 200 tracks. Such an extreme situation may occur if all available tracks within a 250 km × 500 km area must be unified onboard the fighter.

Alignment

A complete alignment of the state vector, typically range, azimuth and elevation is used, and its covariance matrix, requires 1 ms for the onboard sensors and 2 ms for tracks received from the data link. On average 60 ms are required for the first case and 600 ms for the second. A general case was assumed where the sensors provide track updates only, and each sensor has different update times. Therefore the time alignment of all tracks from one sensor to the update time of the other cannot be performed.

Gating and Distance Measure

For the association a three-dimensional pre-gating test and the subsequent calculation of a normalised distance was considered. A complete operation requires up to 0.2 ms. For the first case up to 80 ms and for the second up to 8 s are required.

This is a very unlikely situation, where all tracks belong to the same gate. Any result of the assignment would be very unlikely, due to the amount of the other competing track pairs. Usually a 1.5 dimensional pre-gating test sorts out 80% to 90% of the track-to-track pairs, and the computation time is reduced to 25 ms and 2.5 s respectively.

Clustering

Clustering can be accelerated by bit operations of the processor. A rule of thumb is 0.1 ms processing time for

one track pair. Therefore 40 ms and 4 s must be considered for the two cases.

Clustering is considered to be relevant for the identity fusion, in order to provide suitable subsets for identity conflict examination. For the fusion of kinematic data it is a candidate for omission, because most scenarios are sufficiently resolved by the pre-gating function.

Assignment

The assignment is based on INTEGER operations. Together with an overhead for the conversion of the normalised distance to INTEGER 5 µs for one track pair is a representative figure. For an optimal assignment 40 ms and 40 s processing time for the two cases are maximally required. With a suboptimal algorithm the processing time can be reduced to 6 ms and 0.6 s respectively.

Fusion

After a final assignment of two sensor tracks, the kinematic accuracy can be improved by the fusion of the track data. For the calculation of the state vector of one track together with the covariance matrix 0.5 ms is required. If any track of one sensor correlates with a track of another sensor 10 ms or 100 ms processing time is required.

8 CONCLUSION

The processing time of the two examples were up to 230 ms and up to 50.7 s. This shows that the Sensor Fusion of the three onboard sensors, each providing 20 tracks, can be performed within the typical update time of the sensors. Additionally other fighters, with similar track capacity, can contribute their sensor tracks.

Only the fusion of two complete air pictures or the fusion of an ESM with an extreme reporting capability and an air picture cannot be performed in real time. But this assumes that all 200 tracks are created at the same time and must be fused instantaneously. Such a scenario is very unlikely. Usually new tracks appear subsequently at low rates, and can then be processed. For tracks which are already fused the association rate can be lowered, because it is unlikely that the association result is changed after each track update.

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IMPACT OF COTS ON MILITARY AVIONICS ARCHITECTURES

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SUMMARY

The Department of Defense is being driven to use Commercial Off-the-Shelf (COTS) hardware and software in order to reduce the overly complex and unnecessary practices of using military standards and specifications while reducing costs. There are a variety of issues related to the use of COTS hardware and software components in military avionics systems that have an impact in the architectures. Avionics packaging, cooling, networks, processors, and software languages are just a sample of the areas affected by the use of COTS. A number of steps must be taken by weapon systems managers to ensure they have a strategy in place to meet the challenges brought on by COTS technologies.

INTRODUCTION

The issues surrounding the use of COTS hardware and software in military avionics systems resulted from U.S. SECDEF William Perry's June 1994 Best Commercial Practices (BCP) initiative. This initiative is aimed at reducing the overly complex and unnecessary practices (MIL-STDs, Specs, Testing, etc.) in order to reduce the cost of acquiring and supporting weapon systems.

Early in 1995, a group of engineers from the Avionics Directorate of Wright Laboratory were tasked to study the implications related to the use of COTS on military avionics systems. A number of companies in the defense business were visited in order to get their views on the issues related to the use of COTS on military avionics. The companies visited ranged from electronic device manufacturers, avionics houses, and airframers. A report titled: "Low-Cost Avionics Through Best Commercial Practices" was generated summarizing the results of these visits.

In the area of military avionics, many engineers and managers immediately equate the Perry BCP Initiative to the automatic use of COTS hardware and software, and have begun focusing on detailed design issues related to the use of a particular commercially-available microcircuit or subsystem.

This paper concludes that the use of COTS alone is not the answer to lower avionics systems life cycle cost. From an avionics system perspective, the BCP Initiative should be viewed as a means of *enabling the maximum amount of design, development and testing freedom* possible in order to obtain the lowest life-cycle-cost avionics products from the contractor community. Other conclusions drawn are: COTS hardware and software will be used on aircraft, but as "hybrid" designs; (1) the BCP Initiative supports our ultimate objective of finding the lowest cost COTS, Non-Developmental Item (NDI), or low-risk technology combination capable of doing the job; (2) COTS products, by themselves, are no panacea in solving the avionics cost problem and the introduction of COTS products may bring on another set of problems. These problems include: special provisions for cooling, COTS hardware and software obsolescence, architecture changes to support higher performance and throughput, design changes and immature products brought on by its short time to market cycle, added weight and volume, and an excessive number of "commercial standards;" (3) The majority of COTS avionics products lie in the digital "core" area which constitutes about 1/4 of the avionics fly-away cost of modern fighters, whereas few COTS products are available for the RF and EO/IR sensors, which account for over 1/2 of the avionics cost. Tailoring COTS products, co-production on commercial manufacturing lines and providing the contractors the freedom to be creative by eliminating unnecessary constraints have much higher cost saving potential than a wholesale shift to the use of COTS products alone without a comprehensive cost/benefit analysis.

This paper will address some of the issues related to the use of COTS hardware and software on military avionics and their effect on architectures.

PACKAGING

The harsh operating environments of fighter aircraft have an effect on the electronic packaging of avionics systems. In the past, the full military temperature range (-55 to +125 ^{0}C) has been required for any piece of avionics that reside in the uninhabited area of a fighter aircraft without really measuring the actual temperatures to which the equipment will be subjected during its operational life. The same requirement is imposed on most avionics development programs, even if the equipment is intended for a cargo aircraft relatively benign temperature environment. This requirement alone has driven avionics designers and manufacturers to sometimes over-designing the avionics using expensive MIL-SPEC parts and exotic packaging techniques in order to meet the temperature requirements. Realistic environmental requirements are needed to determine what level of COTS packaging can be used in a particular application. Considerable costs savings can be achieved just by relaxing the avionics operating temperature requirements to allow the designers to use less expensive industrial grade or COTS parts in their avionics designs.

Paper presented at the AGARD MSP Symposium on "Advanced Architectures for Aerospace Mission Systems", held in Istanbul, Turkey, 14-17 October 1996, and published in CP-581.

There is more to considering COTS than just the simple choice of COTS versus custom military parts. There are various grades of parts available. The most common ones will be discussed: military, industrial, and commercial. The top grade is the full military part. It is expected to operate reliably in the harshest environments, over a temperature range of -55 to +125 °C. Packaged in a hermetic ceramic-encapsulated package in order to withstand high humidity levels. These are the highest-priced components, their cost can be 2x to 5x the cost of a commercial equivalent part. They are tested to the fullest extent by the vendor before they are released as products. Normally, they are two or three generations behind the commercially available products. This is due to the fact that parts manufacturers wait until they are getting a high yield out of their manufacturing process for the commercial parts, before they try to qualify the parts for military applications that require the full temperature range operation. The next level is the industrial grade. These components are required to operate over the temperature range of -40 to +85 °C. These parts are 20% less expensive to produce than the full MIL-SPEC parts since testing is not as expensive. Automotive parts are normally a subset of this grade. The last level is the commercial grade. These parts are required to operate from 0 to +70 °C. They offer major advantages in cost, size, weight, performance, and market lead-time; thus they have attracted 99% of worldwide microcircuit sales and are widely used in automotive and computer applications. Commercial grade parts are packaged using plastic encapsulants and are commonly referred to as plastic-encapsulated microcircuit (PEM) or simply, plastic parts. Pure commercial parts are the most available type and almost all new types of electronics parts and upgrades initially come out as pure commercial parts.

The use of COTS parts for military applications has been avoided in the past due to hermeticity problems of plastic parts which resulted in unreliable systems. These problems plagued plastic parts in the early 1970's but have since then been corrected for the most part by the use of new molding compounds and improved manufacturing processes. Many recent studies have proved that PEMs are as reliable or more than ceramic packaged devices easing the introduction of PEMs in military applications.

Operating environmental requirements play a crucial role on the type of electronics parts and packaging that can be used for a given design and application. By specifying realistic environmental requirements, lower cost parts, which meet those requirements, can be used in new avionics designs. Another advantage of using COTS is the availability of higher performance parts and a larger user community.

The warranty for commercial components is for operation between 0 to +70 °C range. Any application that operates outside this range will void the original manufacturer warranty. A variety of packaging approaches can be used to isolate the components from the harsh environments. Exotic packaging technologies like liquid cooling, thermal blankets, or environmental enclosures are available or emerging which can isolate the components from the outside environments. The downside of these packaging technologies is their high cost. High packaging costs can easily cancel the cost savings achieved by the use of less expensive industrial or commercial components.

The size of the electronic modules is another topic of discussion. The military has tried to standardize their electronic modules to the Standard Electronic Module (SEM) size E, or SEM-E. This equates to roughly 6" by 6" of board area. The commercial market standard board size is the 6U VME modules, with a roughly 6" by 9" board size area. In applications where an existing commercial circuit board can be used, the size difference between the preferred commercial and military standards presents a problem. In the older weapon systems which use mostly ¾ ATR size black boxes, the transition to 6U VME size is relatively easy, since the circuit board size is very similar. This situation is different in the case of new weapon systems where the SEM-E size is the standard board size. At this time, several trade studies are underway to compare the benefits and drawbacks of using different electronic module sizes for military applications and what are the life cycle cost implications of both alternatives. There may not be a clear winner in this area and a combination of electronic modules sizes is possible. A hypothetical scenario would be to use commercial standard size electronic modules in the core processor area and SEM-E size modules in the RF area of the avionics.

NETWORKS

A critical area that needs careful attention during the design and development phase is the networks area. They are part of the airframe infrastructure and are very costly to repair, replace, or upgrade. The problem is exacerbated in small airframes where space is at a premium and every effort is made to use any available volume. This is done most of the time by sacrificing the maintainability of the avionics, specially the wiring (networks). There are issues associated with using COTS networks with special purpose militarized avionics, militarized networks with COTS avionics, or any combination of these two options. The different network options will have different impacts in the avionics architecture of new and legacy weapon systems.

There are a large number of COTS networks available for different commercial applications. The applicability of a particular COTS network to a specific avionics design will depend on the functionality required out of the network. It is not always easy to match the capabilities of a commercial network with the requirements of a military application. If requirements and capabilities can be matched, the avionics designer has to worry about how stable the commercial standard is and what is the expected life of the commercial standard. In the past commercial network standards were very stable and had a long life expectancy. This is not true for new networks standards where there are so many available

and the processor technology changes so fast that networks are forced to change in order to keep up with the new technology or they become obsolete and are replaced by whole new designs. This fast pace of change has a tremendous impact on the decision to use a commercial network on military avionics. If a commercial network is selected, there is a high probability that it will have to be upgraded at some point in the life of the system, which will be very costly if it requires massive wiring changes. The use of fiber optic networks mitigates this risk because of the available bandwidth in the fiber. Since fiber optic wires are considerable less bulky and lighter than their copper counterparts, additional wires can be laid out during the manufacturing of the airframe for future use. The use of single mode fiber can provide enough bandwidth for the foreseeable future, where only the optical receivers and transmitters would need to be upgraded to keep up with technology.

The option of using a custom militarized network in combination with COTS avionics presents it's own set of problems. As mentioned earlier, COTS hardware (specially processors) changes at a very fast pace (around every 18 months), so the militarized network will become obsolete at some point in time during the life of the weapon system requiring costly upgrades. Just as in the devices area, it is very costly to develop a network just for military applications. The DoD needs to take advantage of network technologies available in the commercial world where a large user base shares the development costs, making the final product less costly. As explained in the previous paragraph, the problems related to having to upgrade the networks in the future are mitigated by the use of fiber optics cables instead of copper wires.

If a copper-based COTS network is going to be used in a new weapon system, careful attention needs to be given at the location of the wiring in the aircraft to facilitate any future wiring changes. An alternate approach is to include additional wiring in the original design to facilitate upgrades. This is not easy to do in most instances where the avionics are over their weight budget. The use of fiber optics eases the problem because of their lighter weight and volume.

The adoption of new COTS hardware for legacy systems faces the same problem described above. New high performance processors having to move data through old, low bandwidth networks (MIL-STD-1553) can create potential bottlenecks. These bottlenecks, limit the functionality that can be added through the new processors or require expensive wiring changes in order to take full advantage of the new processors. A novel idea in this area is to try to use the existing wiring (mostly MIL-STD-1553 twisted shielded pair) to implement a different network protocol other than MIL-STD-1553. Even though it looks like a good idea, to this day this author is not aware of any successful attempts. Other alternatives include the use of data reduction techniques and even the encryption of data before transmission with decryption at the destination point. These alternatives have been applied successfully eliminating the need for costly wiring changes. One disadvantage of these alternatives is the time required to perform the compression or encryption process.

OBSOLESCENCE

One of the areas causing major concern about the use of COTS is commercial electronics parts obsolescence. As an example, the average turn around time for new processors is down to 18 months. Technology life cycles are being reduced from 21 years for the Transistor Transistor Logic (TTL) to less than 9 years for Advanced BiCMOS Technology (ABT). If this trend continues we can expect to see technology families lasting only 5 to 7 years in the near future. Their life will be shorter than the development cycle of a complex weapon system. This presents a problem for military systems which are generally designed to operate for a life span of 20 to 30 years. A normal weapon system will have to go through 3 or 4 different technology families during its life cycle.

On the other hand, if done right, the use of COTS can eliminate the need for many of the logistic support requirements. If the equipment is highly reliable and low cost, only a small number of spare parts will be required to sustain the system in operation. Upgrades could be available before any failures occur, eliminating the requirements for a complex logistics support structure. The contractors will be required to track obsolescent parts and develop strategies to ensure aircraft will continue to be supplied with parts throughout the life of the aircraft. The contractor would be responsible for the configuration control and the support of the COTS-based avionics. It would be up to him to upgrade his products when they become obsolete. This requires a constant small-scale engineering effort to maintain a current design incorporating the latest technologies.

A new paradigm will be defined in the way we procure and upgrade our avionics systems if we adopt the wide use of COTS in our avionics systems. Instead of having a major avionics upgrade program every 7 to 10 years, new technology and functionality will be added to the avionics system as new technology becomes available and is integrated into the avionics system designs. The contractor responsible for the system will be responsible for ensuring the system performs for as long as he is under contract.

The wide-spread use of COTS devices in avionics designs will require more in the area of obsolescence management to ensure that parts obsolescence do not become an unmanageable problem. The contractor must establish an obsolescence management team. This team will perform detailed obsolescence management surveys of potential suppliers and maintain a data base of the latest survey results. A single point-of-contact for obsolescence notification must be established at each of the subcontractors involved in the program. The team will also monitor the life cycle ratings for

all the active technologies being used in the program. Taking a pro-active role in the area of obsolescence management is crucial for the successful application of COTS in military applications.

SOFTWARE

Military avionics and general COTS software applications are very different. Commercial software companies generate software specialized for consumer and other commercial systems, not for military systems such as weapon system avionics. For the future, little, if any, embedded weapon system software will be COTS. The functions performed by the embedded software are unique to the military. For example, the software allows pilots to destroy hostile targets and avoid destruction by the enemy. However, the use of commercial standards is applicable, especially in the area of programming languages, operating systems, and application programming interfaces.

The use of the Ada language is required by law for DoD weapon systems. This is an impediment for the widespread adoption of COTS for use in new weapon systems. The Ada mandate requires any modification to an existing weapon system where more than 30% of the code will be changed to be done in Ada. This provides an avenue for older weapon systems requiring modifications to use commercial languages instead of Ada. In the case of a new weapon system, the Ada mandate applies since 100% of the software will be generated, it has to be done in Ada.

The problem with Ada lies in the availability and price of Ada compilers, as well as software tools. Since the Ada language has not been widely adopted by the commercial market, Ada software tools and compilers lag the hardware by as much as one year. Due to their limited market, the cost can be 10x the commercial equivalent. The commercial standards for software languages are C and C^{++}, their use is widespread and there are many more software tools available to the programmer. Even Ada programmers are hard to come by and retain since they don't see any future for Ada in the commercial market and they want to stay current in the latest trends in the commercial market.

TESTABILITY

COTS electronic parts in general do not have the levels of testability and built-in test (BIT) that are available in custom militarized electronic parts. Some provisions exist for testability of COTS at the device, board, and system level, but are not adequate to meet the military requirements. In order to meet the more stringent military requirements for fault tolerance and reconfigurability, high levels of testability are required. Some companies are adding special application specific integrated circuits (ASICs) to complement the existing levels of testability available in COTS. Another way to make up for the lack of adequate testability levels in COTS is by performing some of the testability functions in software, which adds complexity to the system. The solution seems to depend on the level of COTS being used. When using COTS at the component level, additional devices can be added to improve testability. At the board and system level, it is more cost effective to improve the testability by the use of additional software. Cost, operational requirements and maintenance strategy will play a role on the amount of testability that is included in designs taking advantage of COTS devices.

THROWAWAY MODULES

The wide use of COTS in military applications has the potential for providing life cycle costs savings in operation support (O&S) by allowing the use of throwaway maintenance. The process to identify the candidates for throwaway maintenance will be the same that is used today to determine the most cost-effective way to maintain an item. A repair-level analysis will be conducted where factors like item cost, predicted reliability, repair cost, support equipment requirements, training, and transportation (among others) are considered as part of the decision process. The lower procurement cost of COTS, along with the fact that the items will be upgraded more often than it is done currently, and the extensive use of warranties should influence the repair level analysis in favor of throwaway maintenance. This can translate into savings in support equipment, personnel, technical orders, and training requirements at the depot or contractor facility. To ensure that good items are not discarded, the levels of BIT need to be sufficient to identify a faulty board with a high level of confidence. The decision to include BIT to identify faults at the circuit level on the board will be left to the contractor. It will be their decision to repair or discard the boards. Discarding the boards will reduce the levels of BIT in the boards, reducing the complexity of the design and the cost.

SYSTEM IMPLICATIONS

A major concern is that if the use of COTS and Best commercial Practices is taken to the extreme, the reduction in contractor guidance could result in a proliferation of custom avionics boxes, electronic modules, displays, etc. which will create an integration and maintenance nightmare, destroy competitive procurements and make common, interoperable avionics (exploiting economies of scale) impossible.

One measure which has the potential of reducing some of these problems is the use of an Open System Architecture (OSA) for future avionics. Definitive guidelines of how OSAs will be employed are currently under review by a DoD task force. The OSA approach is aimed at ensuring the competition and common avionics, through a readily-available set of system specifications that provide adequate information to build interface-compatible hardware and software.

The use of OSAs presents its own set of issues and questions. Will the eventual OSA guidelines require the use of commercial

interface standards for the network design? If so, which ones should be used and should the government play a role in determining which COTS standards should be used or should the contractor decide? What should be the electronic module size? Will detailed connector level standards be imposed to achieve fit compatibility? Is POSIX the right choice for COTS software interface standards and when will these standards be finalized and accepted by the commercial community? Is a hybrid (mixture of COTS and custom) OSA the best choice to meet the performance, reliability, weight and volume needs?

The entire OSA issue is highly complex and will require significant work to make it meaningful. For someone outside the contractor team to be able to build something to operate in the architecture, detailed OSA specifications will be required. For the OSA concept to be useful, a complex build-to specification is needed that provides all the required information that will enable complete physical, electrical, cooling, mechanical mounting, and logical interfacing compatibility with the system. An important benefit of this approach is that it allows proprietary designs and manufacturing methods to be employed below the interface layer. For example, the design of the internal parts of the module is not specified, nor is the actual software code provided.

This new approach to using COTS and Best Commercial Practices giving more freedom to the system designer to make decisions about what will be in the design implies that the Weapon System Contractor will play an even stronger, more vital role than ever in making design and upgrade decisions over the life of the weapon system. They will work with the avionics contractors to establish sub-warranties and approve parts selection and testing plans. The WSC will be ultimately responsible for configuration control and ensuring that COTS obsolescence problems do not occur. Further, the WSC will maintain the flow of parts to and from the field of repair. It will be the DoD responsibility to provide performance requirements early in the program and begin the warranty negotiation process.

CONCLUSIONS

The use of COTS in military avionics architectures has the potential for providing life cycle cost savings if a systems approach is followed. It is important to follow this systems approach from the early phases of the COTS insertion process taking into consideration the diversity of issues described in the previous paragraphs. Numerous trade studies will be required in order to realize life cycle cost savings by making the right decisions for a particular application. As described in the previous sections, the development of a weapon system is a very complex endeavor requiring expertise in a number of different areas. Avionics architectures are the infrastructure of an avionics system and the decisions made during the development of the avionics architecture will have profound impacts on the rest of the avionics system and the avionics contribution to the overall weapon system life cycle cost. There is no exact method to the application of COTS and best commercial practices that can be followed like a recipe. There are too many variables that need to be considered in each particular case, which have the potential for changing the outcome of the different trade studies. A life cycle cost analysis will identify the potential cost savings of a particular approach and the phase(s) where the savings should be achieved (development, production, operation and maintenance).

The weapon systems procurement activities must avoid overspecifying requirements and stop forcing MIL-STD manufacturing processes, 100% parts screening and extensive testing. It is incumbent on the procurement activity to state up-front what the real environmental requirements are and to negotiate, again up-front, a specific set of performance, reliability, weight, volume, cost, etc. parameters from which incentivized warranties can be negotiated. The contractors involved will then be given the necessary freedom to meet the warranty agreement at the lowest cost. This is very similar to the way the commercial market works. Working together as a team, applying a solid systems engineering approach, will facilitate the decision process during the trade studies phase and will ensure the best solution is selected for each particular application.

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An Approach Towards Integration of a Modular Core Avionics System Kernel

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SUMMARY

Daimler-Benz Aerospace (Dasa) Military Aircraft Division has set up an experimental avionic system with modular structure using VMEbus based hardware components and a commercially available operating system (OS) as common OS. Since commercially available realtime OSs do not fulfil the requirements for future avionic systems, *System Management Software* (SYMS) has been developed. SYMS enables the communication between different processor modules and their co-operation. This is the presupposition for fault management and reconfiguration management within the whole core system. The reconfigurability of the experimental system has been demonstrated.

The source code of SYMS has been fully written in Ada. Small sized interfaces to the hardware and to the OS support easy adaptation to different environments of hardware and/or OS. Applications of the whole core system are controlled separately by SYMS Tables ("Blueprints"). The approach supports developing portable and reusable application software.

The flexibility of SYMS enables the demonstration of different standards and their capabilities within different integrated systems. Currently, this work is of interest in view of the Allied Standard Avionics Architecture Council (ASAAC) demonstration programme, planned for the ASAAC Phase II.

Flight capable derivatives of the experimental system can be used in different experimental flight programmes. Information about a modular computer to be flown within an experimental flight programme is presented.

1 INTRODUCTION

Paragraphs 1.1 and 1.2 may be skipped by a reader who is familiar with Modular Avionics. Paragraph 2 summarizes the overall software concept as defined in the "Core Avionics Architecture Concept Definition" /1/ and in the "Modular Avionics Harmonization Study"/2/.

The experimental system is described in section 4. Details about SYMS are contained in section 4.1.

Section 4.2 indicates the present capability of this software, informs about the modular computer and summarizes the benefit of SYMS.

A list of abbreviations is attached.

1.1 Why Modular Avionics?

Since the goals and advantages of Modular Avionics have already been described (see e.g. /3/, /4/), only a short summary of the modular concept is given here:

Basic idea is the common use of a limited number of different modular architectural elements within different functional areas of an avionic system. Modularity concerns the hardware (H/W) as well as the software (S/W). The "inner areas" of an avionic system - excluding specific sensor related parts and the actuators - shall be integrated using the defined limited number of different types of architecture elements. This area called the *core area*. The *kernel* within the core area, as indicated in the title, is understood as an expandable part ("subarea") of the core area. Within a modular integrated core area the data and signal processing (subfunctions) of several avionic system functions shall share a set of common processors.

According to the "Modular Avionics Harmonization Study" /2/ future avionic systems shall have availabilities of 150 hours in a 30 days period. free of maintenance. This shall be achieved by a modular concept enabling increased fault tolerance based on reconfigurability.

Concerning costs, the modular concept shall *considerably* reduce Life Cycle Costs (LCC) for large fleets of A/Cs.

In order to achieve all economical advantages, standardization is essential. - Continuous improvement of avionic systems, however, requires "open" standards. Therefore, a harmonized modular architecture has to prove technological transparency: The concept shall support adoption of new components by easy substitution or adaptation of H/W and S/W.

1.2 Situation in Europe

Modular avionic systems have already been developed in the United States (see e.g. /5/) when European companies were still engaged in concept definitions, for example during the study "neue Avionik Strukturen" (nAS Phase I and Phase II), perfomed in Germany, and during the Allied Standard Avionics Architecture Council (ASAAC) Phase I study, performed by representatives from the United States (US), the United Kingdom (UK), France (F) and Germany (GE). At present, Modular Avionics in Europe is in a prototyping and demonstration phase.

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The goal of the ASAAC study is to define concepts for a future modular avionics architecture with the aim to arrive at *Standardization Agreements* (STANAGs). Within the frame of the ASAAC Phase I study, concepts for future modular avionic systems have been elaborated. These are contained in the "Core Architecture Concept Definition" /1/. A brief summary of /1/ has been published in /6/. Document /1/ has been harmonized and agreed upon by authorised representatives from the governments and industries of the US, UK, F, GE in 1994, and it is regarded as a preliminary basis for further ASAAC activities. These concepts will be assessed and refined in a first stage of Phase II, which is presently in preparation. Phase II will be carried out without US participation; US industry is already engaged in a technology programme referring to the more sensor related areas /7/. During the second stage of ASAAC Phase II, a demonstrator for the core avionics architecture will be built.

Development activities have been initiated in Europe by suppliers collaborating with US companies in order to produce modular architectural elements, for example, Litef with TI and VDO with Harris for data and graphics processor modules, respectively.

Since 1992 several European companies and institutes have also been involved in the Research and Technology Programme No. 4.1 (RTP4.1), belonging to the Common European Programme Area No. 4 (CEPA4) of the European Co-Operation for the Long Term in Defense (EUCLID) - briefly called EUCLID CEPA4 RTP4.1 study - with the title "Modular Avionics Harmonization Study" /2/. This study defines a future architecture based on *emerging technologies*. RTP4.1 is the technological basis for future activities concerning Modular Avionics in Europe. - The use of Commercial-Off-The-Shelf (COTS) components is recommended in /2/ as well as in several other studies and in a memorandum of the US Ministry of Defense /8/.

In the course of the earlier activities, experimental work has also been started at Dasa, for example investigations concerning cooling of modules /9/ or an optical backplane /10/. For earlier activities concerning Modular Avionics (MA) at Dasa, see also /11/. However, none of these works concerned aspects of system integration.

1.3 Tasks Performed

In 1993 Dasa Military Aircraft Division decided to perform the following tasks:

(i) Set up of an experimental system for Modular Avionics using COTS components. This includes the integration of a reconfigurable core avionic system kernel with modular hardware and common system management software and the demonstration of the reconfigurability of the system.

(ii) Based on this kernel: *Development of a modular computer* for use in experimental flight programmes.

The first task was performed in 1993/94 as a Dasa internal study, hereafter also referred to as "first step". The second task was performed government funded in 1995.

2 S/W Concept Defined in Basic Studies

Figure 1 visualizes the S/W concept by means of the three layer S/W model as defined in /1/ and /2/. The figure shows three main S/W layers, namely

- application layer,
- operating system layer and
- module support layer.

The application layer comprises all functional avionic application S/W (indicated as white rectangles) and the common system applications (medium shaded rectangle). The operating system layer (containing the OS, also drawn medium shaded, below) provides the applications with a set of services through an interface, called "Application to Operating System Interface" (APOS). The module support layer (dark shaded) provides the OS with a set of basic services through another interface, called "Module to Operating System Interface" (MOS). In order to manage the actual system configuration the common system applications are provided with the application dependent parameters by means of the "Blueprints". The Blueprints contain information about the system design, system configurations and applications reconfigurations, hence the control of system health and fault management. The APOS, the MOS, the common system applications and the format of the Blueprints shall be standardized.

3 The Experimental System

The *demonstration of a reconfiguration* was defined as a principle part of the first task. For this purpose, a small H/W configuration with a single VMEbus appeared to be sufficient. Reconfigurations concerning the network shall be enabled later.

For the first step, we have regarded the common system applications as a set of basic services for the whole core system, analogous to those performed by an OS in a single processor system. Therefore, we have called them *new services*, and we have allocated them to the OS, "below" the applications (as shown in Fig. 2 - the concept will be described in paragraph 4.1.2). The arrangement supports the adaptability to different OS (see paragraph 4.1.4).

3.1 Definitions and Basic Requirements

Our experiment refers to the capability of common S/W to perform basic functions within the whole core area, supported by a common OS. In this context the term "common" means: The S/W is used by each processor and it is located on each processor. The common S/W - excluding the OS - was called *System Management Software (SYMS)*. SYMS is divided into the *new services* and the *SYMS Tables*. The new services correspond to a subset of the common applications and the SYMS Tables correspond to the Blueprints, as defined in /1/ and /2/, shown in Fig. 1.

The following general requirements had to be fulfilled:

S/W Requirements:

General Requirements for SYMS:

Use of high order language Ada, H/W independence, reuseability, portability, self testability, fault tolerance, support

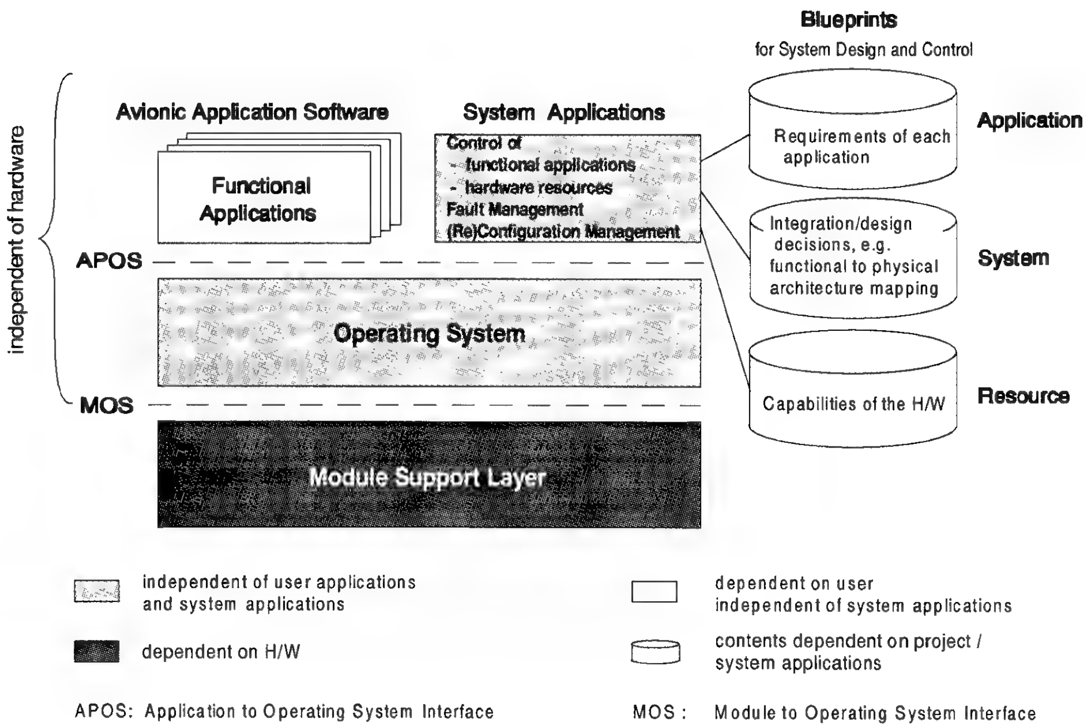


Fig. 1: Software Architecture Layer Model as Defined in the ASAAC and EUCLID Studies

The System Management Software

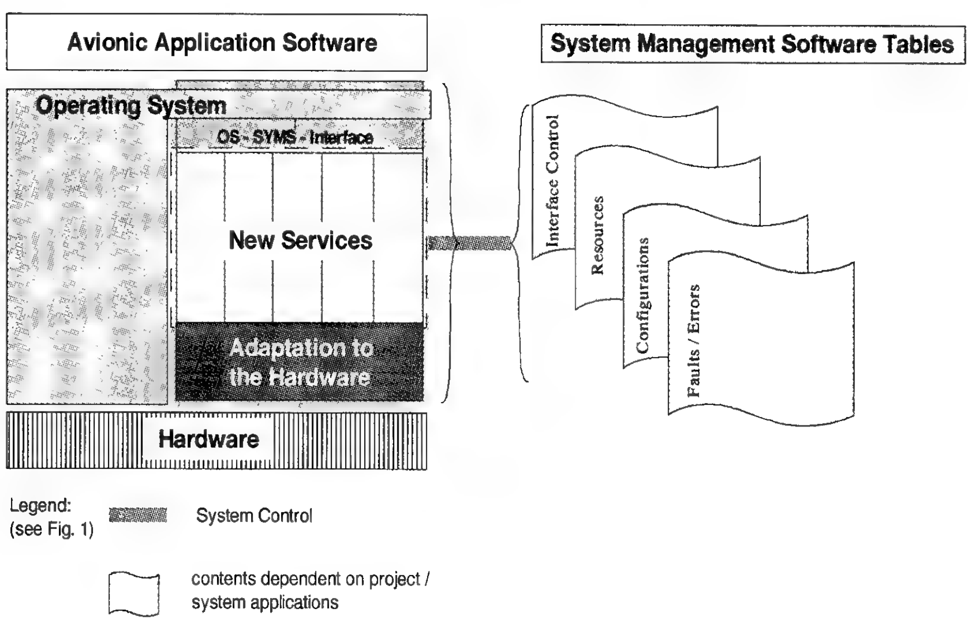


Fig. 2: Arrangement of the System Management Software

of critical areas, support of hard real-time applications; support of application testing and testing of H/W elements.

Requirements for the SYMS Tables:
All dependencies upon avionic application S/W as well as on system related applications (e.g. design and configurations) shall be controlled by the System Management Tables or SYMS Tables. These tables shall be used as input for the new services. The document containing this information is usually known as System Control Document (SCD).

Requirements for the New Services:
Controlled by the SYMS Tables, the new services shall support system-wide test, health management, fault management and (re)configuration management. They shall neither depend on the avionic application S/W nor on the system design, system configurations or on system applications.

H/W - SYMS and SYMS - OS interfaces:
"Small" sized interfaces supporting easy substitution of H/W and/or OS.

H/W:
Modular structure enabling development of common S/W and the demonstration of S/W related capabilities of modular avionic systems.

3.2 Development and Integration

The required S/W was not available. Hence, the major tasks to achieve the first step comprised design and development of SYMS. All details concerning requirements for the modular S/W, its development, capabilities, advantages and possible applications are described in section 4. The requirements listed in the preceding paragraph have been fulfilled for the first step.

SYMS enabled the integration of a reconfigurable system. The block diagramme of the experimental system is shown in Figure 3. The figure shows the H/W structure of the experimental system as set up in the System Prototyping Lab (SPL) at Dasa. The experimental system consists of the three major blocks *Core Avionic System Kernel, A/C simulation* and *work station.*

The *work station* is used for bootstrapping and loading, and this is performed via Ethernet connection.

The block for *A/C simulation* is connected to the kernel system via System Bus Module and MIL-BUS and comprises

- an A/C model (S/W) and a
- cockpit for dynamic flight simulations.

The Core Avionic System Kernel consists of the architectural elements summarized in Table 1. The left column contains types of architectural elements. Column 2 lists the elements used for integration of our experimental system. Brief descriptions and remarks are given in the right column. Available or procured elements are written in small lettes. Developed elements are written in **bold** letters.

The PIbus was *simulated* (written in *Italics* in the table), loaded at run-time. One reason was to achieve compatibility with PIbus based modules, in case such modules become available. The technical reason is: The modular concept requires a message oriented protocol. The VMEbus protocol does not provide these features, whereas the PIbus does. As a result, our VMEbus based system logically works with a PIbus. However, an other message oriented protocol can be used.

Communication between the common applications on different data processors and system reconfiguration has been tested and verified.

3.3 Description of Demonstration

Reconfigurations have been demonstrated repeatedly. At present, reconfigurations of the navigation display (NAV) and primary flight (PF) functions can be demonstrated. During demonstrations the A/C is simulated to be "flown" by a "pilot" sitting in the "cockpit", as shown in Figure 3. The NAV display and the PF functions are "running" (are active) and data from these functions are shown on the displays.

The *initial state,* the state before a module fails, is characterized as follows: Both applications have been distributed on two modules, however, only one is active on *one* module. The other application is "sleeping", i.e. not totally active: The module is provided continuously with the relevant actual status data enabling a rapid continuation of the application in case of a failure ("warm stand by" redundancy).

A *failure state* is simulated by switching off *one* module containing either the NAV or the PF as active application. Then SYMS performs a reconfiguration automatically, and after reconfiguration the system is in a *new, stable state.* In this state the system is able to continue the interrupted application.

The reconfiguration takes less time than the period of a minor S/W cycle, as required for the system (e.g. referring to the modular computer: 20 ms for the TORNADO). Therefore, no interruption is visible on the displays.

Within the rather small configuration of H/W used, this may appear trivial, and further applications should be demonstrated. - However, our SYMS is already capable to manage more general reconfigurations, in an extended H/W configuration. This is described in paragraph 4.2.1.

4 Present and Remaining Benefit

The following sections contain a more detailed description of SYMS in pragraph 4.1; its benefit and already achieved capabilities for further applications are described in the paragraphs 4.2.1 and 4.2.2; a summary of the advantages of the SYMS concept is found in paragraph 4.2.3.

Different H/W and different OS are often used within each subsystem of conventional avionic systems. As a consequence, their avionic application S/W comprises different sets of functions containing different codes for tasks which - in principle - are similar. The dependence of different sets of application S/W on different H/W and OS related environments increases the amount of application S/W to be developed and maintained. Furthermore, these sets are often also dependent on different programmers or on different programming teams.

These disadvantages are reduced or avoided respectively, by means of the modular S/W concept described below.

Relevant Architectural Elements and Interfaces defined e.g. in /1/ and /2/	Elements Used	Remarks
Hardware Expedients Available VMEbus based components and ***simulated PIbus protocol***		
Rack	VME frame.	As used in the lab
Modules	Modules available in the lab, representing Data Processor Modules (DPM) and Graphic Processor Modules (GPM)	Motorola VMEbus based Complex Instruction Set Computer (CISC) processor modules. A one-to-one correspondence to the ASAAC modules is not required for the first step. Other COTS or ROTS H/W can be used
Networks	MIL-STD-1553B as A/C system bus	Was available and required for an experimental flight application
	VMEbus as "rack internal" communication network	*PIbus protocol as described in /12/, simulated* on VMEbus, loaded at run-time. Other message oriented protocol can be used
Software Available and **developed** architectural elements		
Module Support Layer	**SYMS - H/W - Interface, H/W dependent part of SYMS**	1) Network suppport (to be regarded as part of the MOS; here: Adaptation to the VMEbus) 2) *PIbus simulation* and a Special Device Driver for the MIL-STD-1553B
Operating System	ARTX	Available Ada realtime executeable Off-The-Shelf kernel from Ready Systems. Other OS can be used
APOS	**SYMS - OS - Interface, OS dependent part of SYMS**	OS dependent part of new services, according to /1/ and /2/ required as part of the APOS, between all applications and the OS
Common System Applications	**Part of SYMS, handled as "attachment" of the ARTX**	New services, according to /1/ and /2/ required (at least partially) in a layer "above" the APOS
Blueprints	**SYMS Tables**	contain system control data as input for the new services
Avionic Application S/W	Navigation Display and Primary Flight functions	Available S/W, used to demonstrate reconfigurations

Table 1: Architectural Elements Used for Integration of the Core Avionic System Kernel (see also Layer Model, Fig. 4)

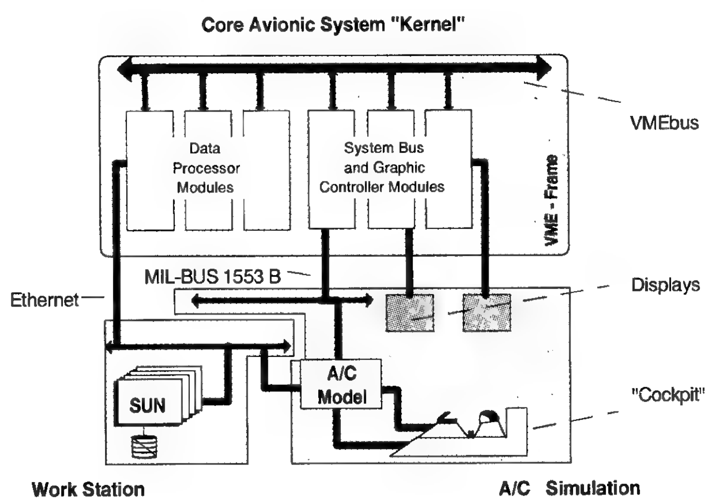


Fig. 3:
Block Diagramme of the Experimental System

4.1 The System Management Software

4.1.1 S/W Requirements

SYMS has been developed in compliance with the following S/W requirements:

(1) The new services shall have a generalized capability to detect errors.

(2) The new services shall not depend on the H/W.

(3) The new services shall be applicable for several system applications within any system configuration formed by the H/W shown in Figure 3 and listed in Table 1. Adaptation to other H/W and OS shall be possible without major difficulties. The new services shall be able to support the management of the application S/W in other environments due to H/W and/or OS.

(4) Different system configurations can comprise different configurations of
- H/W modules,
- application S/W modules,
- special interface modules for H/W and S/W and
- different locations of the application S/W on the modules.

(5) The SYMS Tables shall be edited in a fixed format.

The requirements (1) and (2) and (3) *enable and enforce* designing and coding of application S/W in a flexible, generally applicable code, independent of any specific H/W related requests.

Each of the possibilities indicated in (4) and their combinations describe different states of the system. Each state can be represented by a set or subset (table or "subtable") of data within the SYMS Tables. Subsequent states of the system are controlled by subsequent tables. (Therefore these tables have been called "Blueprints".)

4.1.2 SYMS Concept

Our concept is shown in Figure 4. The SYMS is drawn grey shaded and comprises the following major parts, as indicated in the figure by numbers:

1. A layer serving as interface to the OS, the SYMS - OS - interface.
2. The new services.
3. A layer used as interface to the H/W, the SYMS - H/W - interface.
4. The SYMS Tables.

The SYMS Tables are drawn in another ("softer") shape indicating *variable contents.*

4.1.3 The New Services

The package of new services comprises the following functions:

Input Converter (C_I):
C_I converts the received data into the format required by each user application.

Output Converter (C_O):
C_O converts the outgoing data from the application related format into a transmittable format.

Error Handler (ER):
ER checks the integrity of the system and initiates suitable actions in case of problems. Using the data in the SYMS Tables, ER can find errors caused by exceeding the upper limits of different resources, e.g. due to memory, capacity, processing load ...

Message Manager (MM):
The user application provides to MM the name of data to be transmitted. By means of the SYMS Tables, MM interpretes interface control information from the SYMS Tables and initiates further control and actions. Further actions concern the

- distribution of different control data to the other services, such as transmission of conversion commands for the data of each application to C_O and C_I ,
- destination of the data,
- structure of the data,
- route to the subsequent device.

Special Functions (SF):
SF comprises a collection of functions, such as

- system applications to support the use of the SYMS Tables concerning the installation of device drivers to manage dedicated system H/W and
- the reconfiguration management functions.

4.1.4 Interfaces to the H/W and to the OS

The SYMS - H/W - Interface

Two possibilities of transfer to the H/W have been implemented, a *general access* and an access via *special device driver* (SDD).

The general access is performed via controlled access to other boards, containing the same SYMS. The data are guided to (from) the real H/W

- via *PIbus Emulation* offering a standardized device handler, providing a message controlled transmission of the data and subsequent
- adaptation to the H/W (or vice versa respectively,) by conversion of the PIbus requirements to the real bus accesses.

SDD's are required for the integration of devices which do *not* provide the facilities to comply with the H/W requirements of the PIbus protocol, such as handshaking.

The SYMS - OS - Interface

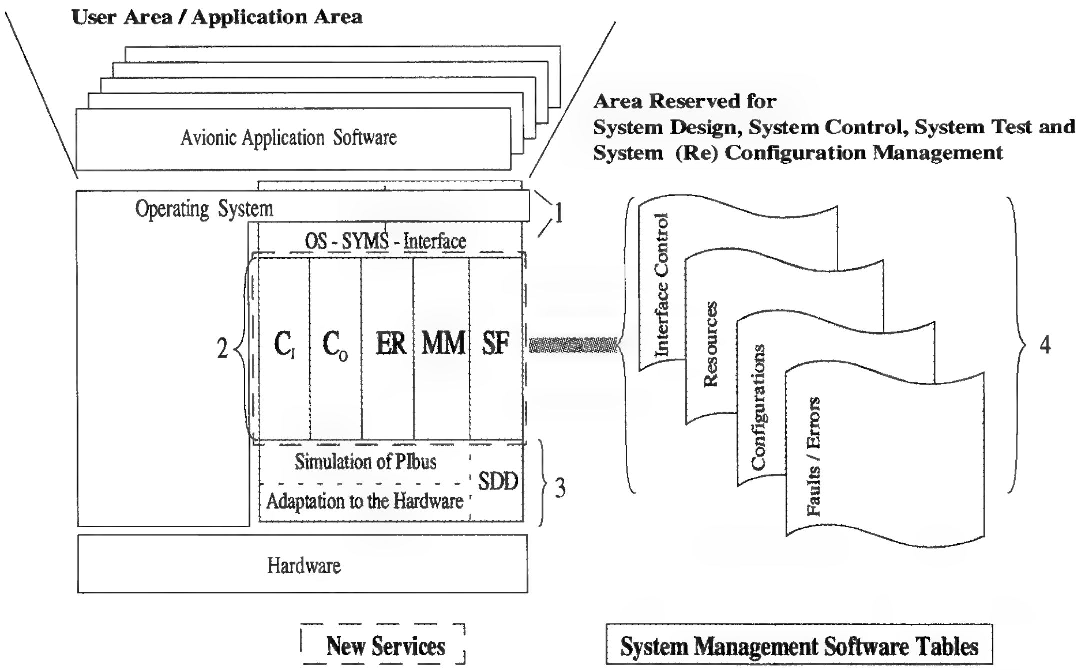
The SYMS - OS - Interface consists of two small sized layers, as shown in Figure 4 (indicated by number 1).

The upper converts a call from the application S/W into an OS call.

The lower layer is the interface between the OS and SYMS. Here, the resulting OS function is converted into a call of a SYMS function.

An attachment of our new services to an existing OS seems natural and logical since the OS is responsible for their administration.

The System Management Software



Legend

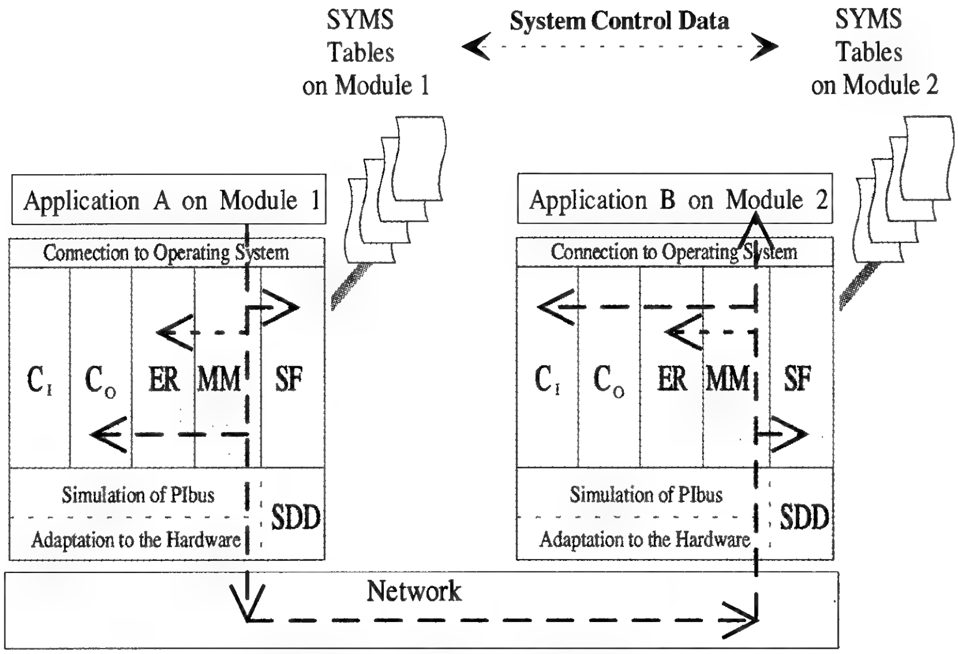
System Management Software (SYMS)

1 Connection to the Operating System
2 New Services
3 Connection to the H/W, the SYMS - H/W - Interface
4 SYMS Tables

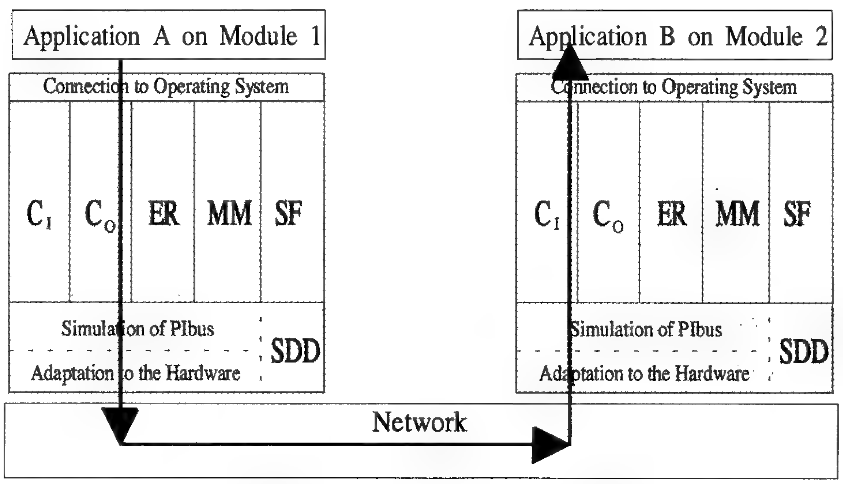
System Control

C_I	Input Converter	SF	Special Functions
C_O	Output Converter	SDD	Special Device Driver
ER	Error Handler	MM	Message Manager

Fig. 4: The System Management Software



Primary Control Flow for the Data Transport
From Application A on Module 1 to Application B on Module 2, as shown below



Data Flow From Application A on Module 1 to Application B on Module 2

Legend

System Control (Here: "Leads the path" from A to B. This path is dependent on system applications. A does not need to "know" the destination)

Data Flow

Primary Control Flow for Data Transport
Control Flow in Case of Errors

C_I	Input Converter	SF	Special Functions
C_O	Output Converter	SDD	Special Device Driver
ER	Error Handler	MM	Message Manager

Fig. 5: Control Flow and Data Flow During Data Transport

4.1.5 The SYMS Tables

The SYMS Tables contain the whole System Control Document (SCD) and they consist of the following four major tables:

Interface Control Document (ICD):

The ICD contains a description of all data paths from the user application to the "outside world" and vice versa. This information concerns, for example, the location of data, the types of data, conversions to be performed. Data elements of each application are represented in the ICD by different entries.

The ICD is used by C_I und C_O.

Resource Tables:

The resource tables contain the information about *all* types of resources to be used.

The resource tables are used by MM.

Configuration Tables:

The configuration tables contain

- references about the connections to be enabled by means of the ICD table entries,
- a description of the actual configuration (actual state) of the system,
- system states to be enabled by reconfigurations.

The configuration tables are used by MM and SF.

Fault and Error Tables:

The fault and error tables contain a list of possible errors, faults or other erroneous states to be found and a list of consecutive actions to be initiated.

The fault and error tables are used by ER.

4.1.6 Description of a Simple Data Transfer

The co-operation of the new services by means of the SYMS Tables is indicated in Figure 5. The figure indicates the paths of control data (upper half) and the data stream (lower half) during data transfer from module 1 to module 2. In the following text terms like "application A on module 1" or "module 1, application A" are written as "A(1)" ; "ER on module 2" is written as "ER(2)".

The data transfer is managed by the following control flow:

Control Flow on Module 1:

A(1) has finished processing and sends to MM(1) control information enabling the initiation of correct actions.

MM(1)

- decodes the control information,
- contacts SF(1) to get the actual control information from the configuration tables(1),
- contacts ER(1) in case an error is detected and
- hands over the actual control information for data conversion from the ICD(1) to $C_O(1)$.

MM(1) generates the information for further routing of the data to be transported by means of the resource tables(1) and the configuration tables(1).

In the meantime, the data stream has reached $C_O(1)$ and has been converted. Now the data are provied/ transmitted through the

- layer "Simulation of PIbus(1)" and "Adaptation to the Hardware(1)"
- network and subsequently through the
- layer "Adaptation to the Hardware(2)" and "Simulation of PIbus(2)"

to $C_I(2)$. This includes the transfer of the control message, routed to MM(2).

Control Flow on Module 2:

MM(2)

- decodes the control information,
- contacts SF(2) to get the actual control information from the configuration tables(2),
- contacts ER(2) in case an error is detected,
- hands over the actual control information for data conversion from the ICD(2) to $C_I(2)$.

Now, the data transfer will be completed: $C_I(2)$ converts the received data into the format and structure required by B(2) and finally, the data are provided to B(2).

4.2 Remaining Benefit and Possible Applications

4.2.1 Reconfigurability

SYMS supports a flexible system design. Any sequence of reconfiguration can be determined by the SYMS Tables. This sequence depends on the priority of the applications (S/W modules), for example on their criticality; and the arrangements of the applications on the H/W modules depend on the defined priority. All this will depend on mission profile of the A/C. The applications can be located several times on different H/W modules. Different system configurations may be preferred in each mission phase. Based on the defined sequences, different reconfiguration schemes may be applied.

The demonstration of a reconfiguration, as described in paragraph 3.3, shows only a limited application of SYMS. Therefore, in this paragraph, the preliminary reconfiguration concept is described in order to explain the capabilty of SYMS already achieved.

Currently, in our experimental system, error detection is restricted to a basic check of the presence or reaction of a module caused by errors due to the bus protocol. Fault management concerns the analysis of faults concerning communication between modules, and the error analysis is restricted to the identification of faulty H/W modules. - However, our SYMS can already contribute to increasing system availability. This is shown by means of an abstract example, which might appear as a play; but we believe, such concepts will be practicable und useful for avionic systems of the next generation.

A system consisting of five H/W modules and the applications A, B, C, ... , P, as shown in Table 2b on the next page

Table 2 a: Example 1: ***Conventional*** System with 3 Modules - One Failure (on Module 1)

Module	Distribution of Applications														
	A	B	C	D	E	F	G	H	I	K	L	M	N	O	P
1	*	*	*	*	*										
2						*	*	*	*	*					
3											*	*	*	*	*
State After Failure on Module 1															
~~1~~	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---
2						*	*	*	*	*					
3											*	*	*	*	*
Result: Degradation or "system crash" (dependent on distribution of applications)															

Table 2 b: Example 2: ***Modular*** System with 5 Modules - One Failure (on Module 1)

Module	Application - Initial State														
	A	B	C	D	E	F	G	H	I	K	L	M	N	O	P
1	$\underline{*}$	$\underline{*}$	$\underline{*}$	(*)		(*)	(*)			(*)		(*)	(*)		
2	(*)			*	*	*	(*)	(*)			(*)		(*)	(*)	
3	(*)	(*)			(*)		*	*	*	(*)				(*)	(*)
4		(*)	(*)	(*)				(*)	(*)	*	*	*			(*)
5			(*)		(*)	(*)			(*)		(*)	(*)	*	*	*
State After Failure of Module 1 and Successive Reconfiguration															
~~1~~	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---
2	$\underline{*}$			*	*	*	(*)	(*)			(*)		(*)	(*)	
3	(*)	$\underline{*}$			(*)		*	*	*	(*)				(*)	(*)
4		(*)	$\underline{*}$	(*)				(*)	(*)	*	*	*			(*)
5			(*)		(*)	(*)			(*)		(*)	(*)	*	*	*
Result: Full system availability after reconfiguration															

Table 2 c: Example 3: ***Modular*** System with 3 Modules - One Failure (on Module 1)

Module	Application - Initial State														
	A	B	C	D	E	F	G	H	I	K	L	M	N	O	P
1	$\underline{*}$	$\underline{*}$	$\underline{*}$	$\underline{*}$	$\underline{*}$	(*)	(*)	(*)	(*)	(*)	(*)	(*)	(*)	(*)	(*)
2	(*)	(*)	(*)	(*)	(*)	*	*	*	*	*	(*)	(*)	(*)	(*)	(*)
3	(*)	(*)	(*)	(*)	(*)	(*)	(*)	(*)	(*)	(*)	*	*	*	*	*
State After Failure of Module 1 and Successive Reconfiguration															
~~1~~	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---
2	$\underline{*}$	(*)	$\underline{*}$	(*)	$\underline{*}$	*	*	*	*	*	(*)	(*)	(*)	(*)	(*)
3	(*)	$\underline{*}$	(*)	$\underline{*}$	(*)	(*)	(*)	(*)	(*)	(*)	*	*	*	*	*
Result: Full system availability if modules 2 and 3 will not be overloaded. Otherwise: Degradation. This can be avoided by a suitable system design.															

Legend:

- * Application is active; (*) Application is "sleeping";
- $\underline{*}$ Application will be affected by failure of module 1 / has been activated after reconfiguration on other module
- --- Module has been logically disconnected

Table 2: System Availability in Case of Failures for a Conventional and Two Modular Systems (Examples)

shall be assumed (example 2 in the middle of the table). The first columns contain the number of each module. The location of different S/W applications on these modules is indicated in the following columns. The upper half of the table shows the initial state of the system, and the lower half shows the state after reconfiguration due to a failure on module 1.

Preliminarily, we have decided to locate each application three times, on three different modules - as indicated by the stars - and we have assumed: All applications require about the same processing load and all H/W modules are identical. (Otherwise, another distribution of applications should be applied.) Our concept shall be explained by means of a failure on module 1, and this concerns mainly the columns A, B, C and D.

Initially, each application is active *once on one module*. In our example, the applications A, B and C are all active on module 1, as indicated by the underlined stars. The initially active arrangements have been called *first arrangement*s of an application. Furthermore, A, B and C are also located on the other modules, however, "sleeping", as explained in paragraph 3.3. This is indicated by the stars in brackets. If a first arrangement is affected by a failure, the "sleeping" arrangements are activated by reconfiguration in a sequence defined in the configuration tables. The successors of the first arrangements have been called second (third, ...) arrangements.

For completeness, the presuppositions are listed here:

- a message oriented protocol shall be used,
- errors of the transport medium are excluded,
- the fault shall occur during data or message transfer from application A on module 1 to application D on module 2.

In the following text a term like "ER on module 2" is written as "ER(2)" and a term like "application A on module 1" or "module 1, application A" is written as "A(1)".

The failure is detected either by MM(1) or by MM(2) and "reported" to ER(1) or ER(2), respectively. By means of data from the ICD Tables(1 or 2), ER(1 or 2) "knows":

Module 1 and module 2 - more precisely, A(1) and D(2) - are directly involved. Now ER(1 or 2) initiates a voting between further involved modules. This information is contained in the configuration tables. Further involved are all those modules which are related with these modules containing arrangements of each application. In our example, the modules

- 1 and 2 and 3 are related due to application A and
- 1 and 2 and 4 are related due to application D.

This defines the two sets of modules {1, 2, 3} and {1, 2, 4}.

A 2 : 1 voting can be performed by the sets {1, 2, 3} or by {1, 2, 4} or by both. The fault will be located, and the reconfiguration can be performed. One of the - non faulty - ERs initiates the isolation of the faulty module. All erroneous states and data caused by the identified error will be eliminated. The relevant SYMS Tables on *all* modules will be updated, and the system will continue in a new, well defined and stable state. After reconfiguration, the system is full available tolerating the faulty module.

Our fault management concept is expandable to include further system resources. The error analysis could be refined in order to identify faults caused by application S/W modules.

4.2.2 SYMS in HIMA

The modular computer shall be used in different experimental flight programmes. The first configuration, called HIMA (for Helmet Mounted Display Integrated Modular Avionics) will be used in the Helmet Mounted Display (HMD) Experimental Programme.

Integration of HIMA is based on the use of the same SYMS, OS and H/W as the experimental system. An extended SYMS will be portable from the experimental system to HIMA at any time, without major difficulties. A housing has been built for installation of HIMA into the TORNADO A/C which will be used for the HMD flight experiments. HIMA is shown in Figure 6.

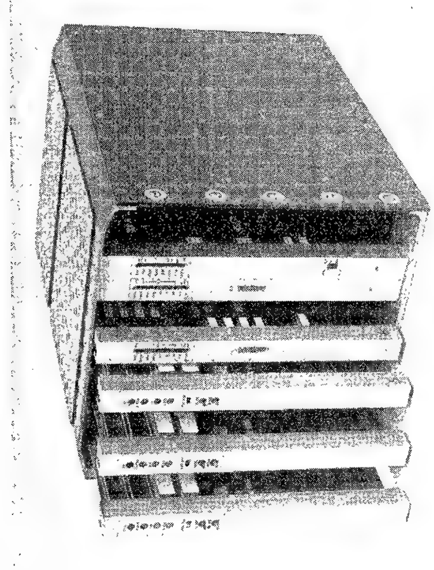


Figure 6: HIMA - The Modular Computer for Experimental Flight Programmes

An improved experimental system, including an extended SYMS, and another OS, for example a UNIX OS can serve as basis for further flight applications.

4.2.3 Summary of Benefit Due to SYMS

The costs for design, development, test and maintenance of S/W have increased tremendously during the last decades, and this can be no longer tolerated. The modular S/W concept - as a major part of the system concept - will contribute to the reduction of LCC remarkeably. The advantages and the benefit of the modular S/W concept can be summarized with reference to SYMS as follows:

The modular S/W concept with SYMS supports

- developing reusable application S/W which is independent of the H/W, because these dependencies are managed by the SYMS Tables and performed by the new services.
- reducing effort for design and coding application S/W modules, as apart from satisfying common interfaces, programming is independent of system design, system applications and system configurations.
- consistency checking during system design by standard design support tools, because the system design is controlled by the SYMS Tables, and these are written in a standard format.
- testing application S/W due to the reduced number of different interfaces.
- system testing and system verifying with a reduction in the number of different test facilities, and the SYMS Tables can be tested/verified separately.
- maintaining S/W due to the more uniform design and the reduced number of different maintenance tools.
- S/W upgrading/extending by substitution/adding of S/W modules.
- redesigning existing systems and designing/updating new systems.

Considering the amount of common S/W required on each module and the several ("warm stand by") redundant arrangements of applications, these advantages have to be balanced against an increased demand for storage capacity, administration effort and reduced system performance. However, these disadvantages will become less important, since

- the S/W applications - and this is the major part of all S/W - do not need to perform administration functions, because these are performed by the SYMS,
- H/W modules with a much higher performance and with increasing storage capacity are expected to be available in the future,
- the price for H/W modules, hence for storage capacity, is still decreasing,
- a conventional (non modular) concept will not allow the redistribution of application S/W on different H/W modules within the whole core system.

Therefore, we believe: With a practicable effort, only the modular concept will enable the achievement of the required system availability of 150 hours in a 30 days period, free of maintenance.

It is a long way to the fully standardized Modular Avionics. The development of SYMS is an important first step.

5 Results and Conclusions

Our concept is a suitable approach towards integration of future core avionic systems. An extendable package of System Management Software has been developed. The SYMS Tables and the new services comprise fully portable S/W. The concept enforces and supports the development of portable and reusable application S/W.

SYMS should be extended and qualified for use in future upgrade programmes.

The flexibility of our SYMS - OS and SYMS - H/W - interfaces is an important feature in view of the ASAAC demonstration programme: The adaptability will support the integration of other H/W and/or OS. This will allow the demonstration of capabilities of different architectural elements and standards.

On the other hand, as long as the new standards are not established, the concept allows the development and integration of reconfigurable systems, based on COTS. System qualification should be based on a qualified extended SYMS and on qualified Ruggedized-Off-The-Shelf (ROTS) components. System test will be facilitated by means of a refined SYMS.

Similar approaches should be considered for application in other future aerospace systems.

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ABBREVIATIONS

A(n)	Application S/W module A, located on H/W module n, n = 1, 2, 3, ...
APOS	Application to Operating System Interface
ARTX	Ada Real Time Executable Run Time System (COTS OS from Ready Systems)
ASAAC	Allied Standard Avionic Architecture Council
A/C	Aircraft
CEPA	Common European Programme Area
C_I	Input Converter
C_O	Output Converter
$C_{I/O}(n)$	Input Converter or Output Converter, located on H/W module n, n = 1, 2, 3, ...
CISC	Complex Instruction Set Computer
COTS	Commercial-Off-The-Shelf
Dasa	Daimler-Benz Aerospace
debis	Daimler-Benz Inter Services
DPM	Data Processor Module
ER	Error Handler
ER(n)	Error Handler, located on H/W module n, n = 1, 2, 3, ...
EUCLID	European Co-Operation for the Long Term in Defense
F	France
GPM	Graphic Processor Module
GE	Germany or German
HIMA	Helmet Mounted Display Integrated Modular Avionics
HMD	Helmet Mounted Display
H/W	Hardware
ICD	Interface Control Document
LCC	Life Cycle Cost
LME	Luftfahrt, Militärische, Entwicklung (development department of Dasa Military Aircraft Division)
MA	Modular Avionics
MIL	Military
MM	Message Manager
MM(n)	Message Manager, located on H/W module n, n = 1, 2, 3, ...
MOS	Module to Operating System Interface
MULTICS	Multiplexed Information and Computing Service
nAS	neue Avionik-Strukturen (GE study programme)
NAV	Navigation Function (S/W application)
OS	Operating System
PF	Primary Flight Function (S/W application)
PI	Parallel Interface or Processor Interface
RTP	Research and Technology Programme
ROTS	Ruggedized-Off-The-Shelf
SCD	System Control Document
SDD	System Device Driver
SF	Special Functions
SF(n)	Special Functions on module n, n = 1, 2 ...
SPL	System Prototyping Lab (at Dasa LME in Munich)
STANAG	Standardization Agreement
SYMS	System Management Software
SYMS(n)	SYMS, located on H/W module n, n = 1, 2, 3, ... H/W module n, n = 1, 2, 3, ...
S/W	Software
UK	United Kingdom
UNICS	Uniplexed Information and Computing Service
UNIX	(see UNICS; Bell Labs trade name for a system derived from MULTICS and UNICS)
US	United States (of America)
VME	Versatile Module Europe

LOW-LEVEL FLIGHT CAPABILITY OF A FUTURE MILITARY TRANSPORT AIRCRAFT BASED ON COMMERCIAL AVIONICS

by
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SUMMARY

There is a need for a new military transport aircraft, which can cope with the operational requirements to improve the current airtransport forces of the European countries to satisfy tactical, logistic and future operations, at the beginning of the next century.
Significant requirements, which relate to the avionics and mission systems, are for instance:

- o low-level flight capability and
- o board-autonomous approach and landing capability

enabling adverse weather operations by day and night.

This paper describes a system concept for low-level flight capability based on commercial avionics as used in AIRBUS aircraft. First, the essential functions and features of the flight control and flight guidance system are highlighted. Then, the additional functions and system elements related to controls/displays and operational modes, which are required for low-level flight, are discussed. Finally, the first results of a demonstration and pilot evaluation performed in the flight simulator at DAIMLER-BENZ AEROSPACE AIRBUS in Hamburg are presented.

The investigations described in this paper have been performed within the context of technology studies, which are partially sponsored by the German Ministry of Defence.

LIST OF ABBREVIATIONS

AFCS	Autoflight Control System
AGL	Above Ground Level
AOA	Angle of Attack
AP	Autopilot
ATHR	Autothrust
BARF	Basic Airworthiness Requirements File
EFIS	Electronic Flight Information System
FbW	Fly-by-Wire
FCS	Flight Control System
FCU	Flight Control Unit
FD	Flight Director
FMS	Flight Management System
FPA	Flight Path Angle
ft	feet
GNSS	Global Navigation Satellite System
HDD	Head-Down Display
HUD	Head-Up Display
IRS	Intertial Reference System
LDG	Landing
L/G	Landing Gear
MCDU	Multipurpose Control and Display Unit
MSA	Minimum Sector Altitude
MSL	Mean Sea Level
ND	Navigation Display
PFD	Primary Flight Display
RA	Radio Altitude
SCH	Set Clearence Height
TOC	Top of Climb
TOD	Top of Descent
TOW	Take-off Weight

1. DEFINITION OF "LOW-LEVEL FLIGHT"

Flights are defined as "low-level", when performed with

- o jet aircraft below 1 500 ft above ground level (AGL)
- o propeller aircraft or helicopters below 500 ft AGL.

Low-level flights are performed for reasons of self-protection against threats (e.g. hostile sensors or anti-aircraft defence) by means of terrain masking. In fact low-"level" flight profiles are trajectories representing a combination of terrain-following and terrain/threat-avoidance segments.
But there are also important low-level applications outside hostile environment, as for instance, assistance or emergency flights (e.g. para-dropping in low-ceiling weather conditions).

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2. FLIGHT GUIDANCE SYSTEM OF A COMMERCIAL AIRCRAFT

The realization of the future military transport aircraft will be performed correspondent to a commercial approach. This means, for instance, that the aircraft design is based on the Basic Airworthiness Requirements File (BARF) and AIRBUS rules, completed by additional military requirements. Therefore it is necessary to investigate the suitability of commercial avionics to cope with the operational requirements ("dual use").

The flight guidance system of a modern commercial aircraft consists of the following major components:

- o Electronic Flight Control System (Fly-by-Wire - FbW)
- o Autoflight Control System (AFCS)
- o Flight Management System (FMS)
- o Flight Guidance Information (Primary Flight Display - PFD, Navigation Display - ND)
- o Navigation Sensors.

These components form three control loops as shown in Figure 1.

According to the operational mode selected by the crew the aircraft can be piloted either manually via the Fly-by-Wire System, or temporarily automatically during certain flight phases via the Autoflight Control System or completely automatically during the whole flight via the Flight Management System.

2.1 Fly-by-Wire System (FbW)

An Electronic Flight Control System (Fly-by-Wire) can be characterized by the following features:
Pilot's control inputs are transmitted by means of electrical signals. Flight control computers transform the control inputs into control surface commands. The flight control computers also contain stabilization functions, as for instance:

- o Auto Trim
  The Auto Trim function keeps the commanded load factor (flight path angle) constant and adjusts the angle between elevators and vertical stabilizer to zero.

- o Turn Compensation
  The Turn Compensation function keeps the flight path angle constant during turns.

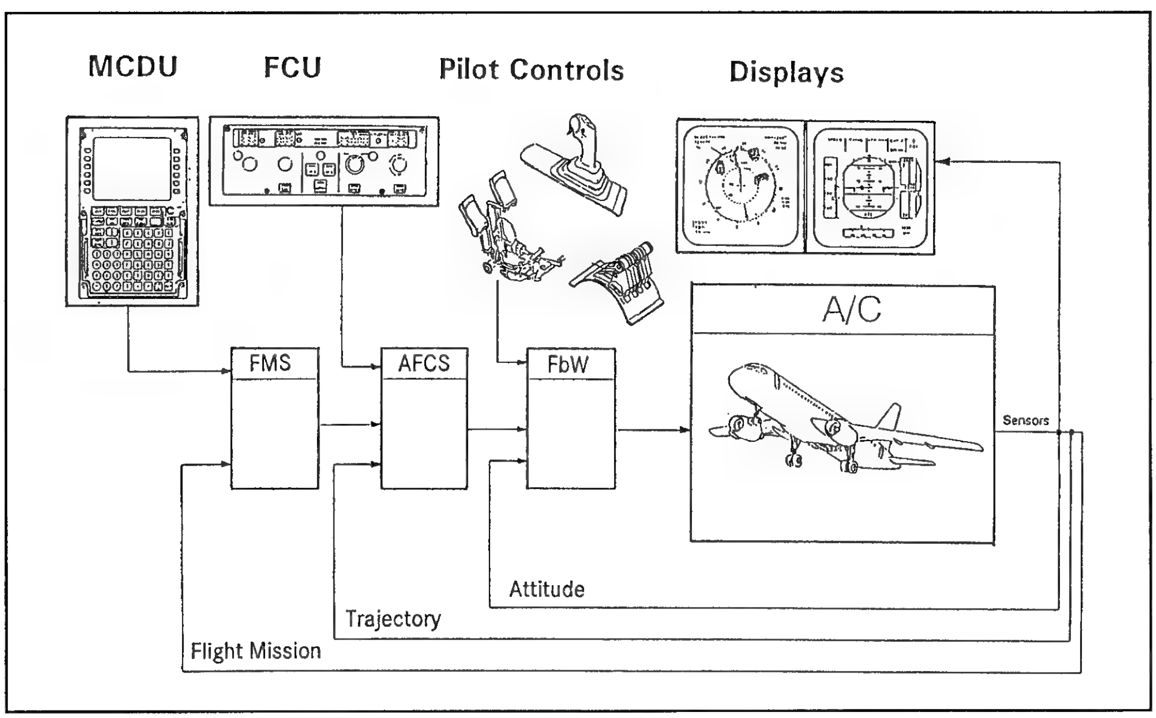

FIGURE 1: Components of a Modern Commercial Flight Guidance System

o Turn Coordination
The Turn Coordination function permits a slip-free flight, i.e. turns don't need to be supported by peddal commands.

o One Engine Out Compensation
When an engine failure occurs, this function prevents from unintended yawing of the aircraft.

o Yaw Damping
to control the aircraft's own dynamic modes.

Additionally the flight control computers contain monitoring functions (envelope protections) to keep the aircraft within its operational limits. These are:

o High Angle of Attack Protection
For low-speed flight phases the angle of attack (AOA) will be kept below the stall range.

o Manouver Protection
For reasons of structural integrity the commanded load factor (vertical acceleration) will be kept within the permissible range.

o Overspeed Protection
An excessive high-speed condition might result in structural failure or loss of control due to high air loads, vibration, flutter or shock waves. The aircraft ist protected from entering an excessive high-speed flight regime by an automatic thrust reduction and an initiation of a climb (positive load factor command).

o Attitude Protection
This protection prevents the aircraft from achieving excessive pitch and roll attitudes.

2.2 Autoflight Control System (AFCS)

The Autoflight Control System (AFCS) consists of the components:

o Autopilot (AP)
o Autothrust (ATHR)
o Flight Control Unit (FCU).

The Autopilot contains functions, which permit to guide the aircraft along selected courses and/or at selected altitudes and to perform climbs, descents or approaches.

The Autothrust (ATHR) functions permit to keep selected speeds or thrust levels.

The nominal values of the corresponding flight parameters can be provided in two different ways:

o Manual selection via the Flight Control Unit (FCU) "Selected Guidance".

o Provision of nominal values by the Flight Management System (FMS) "Managed Guidance".

The aircraft can be piloted either automatically ("AP Engaged") or manually ("AP Disengaged") on the basis of Flight Director (FD) information, i.e. indicated commands, which are provided by the Autopilot.

The FD information is displayed on the Primary Flight Display (PFD).

2.3 Flight Management System (FMS)

The essential elements of a Flight Management System are:

o Flight Management Computer including Navigation Data Base and Performance Data Base

o Multipurpose Control and Display Unit (MCDU) for data input.

Two FMS functions are important with respect to flight guidance (Figure 2):

o Flight Planning
- Flight Plan Stringing
- Performance Calculation

o Flight Plan Execution
- Navigation
- Vertical Guidance

2.3.1 Flight Plan Stringing

The (horizontal) flight route between departure and destination airports has to be constructed. For this purpose airline defined company routes or route elements, e.g. runways, airways, nav aids, waypoints, etc. are available in the navigation data base.

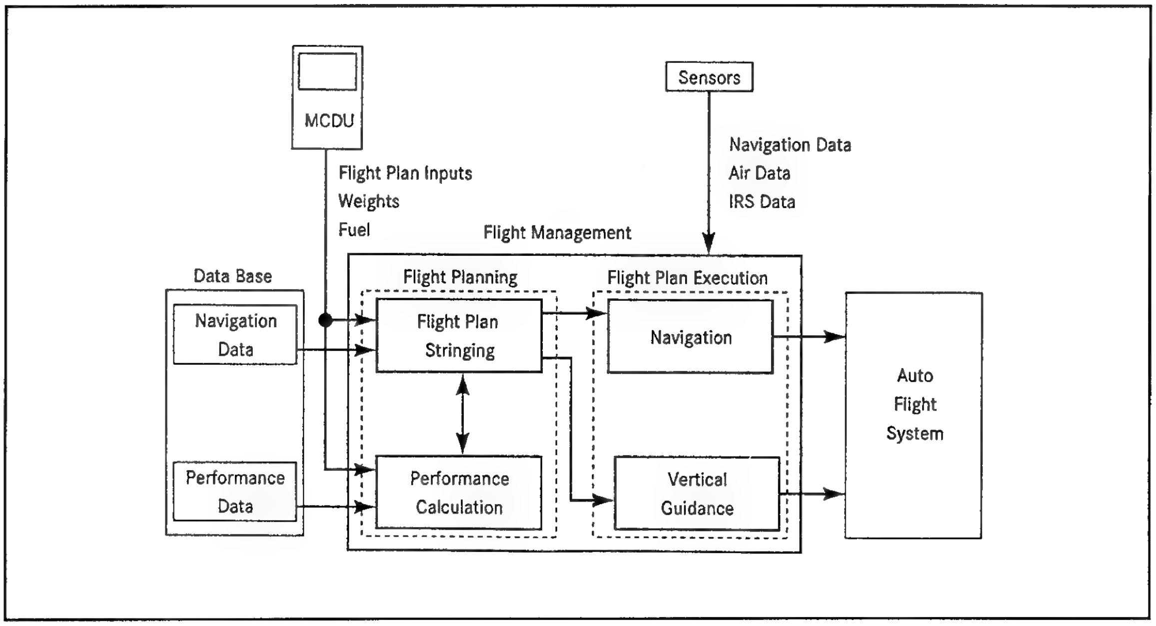

FIGURE 2: Flight Management System (FMS) Functionality

2.3.2 Performance Calculation

The vertical flight profile is calculated taking into account the following parameters:

- o Take-off Weight (TOW)
- o Air Data (Wind, Temperature) of candidate flight levels
- o Cost Index
  The cost index, which in commercial air transport is determined individually by each airline, is the optimization criterion.

Results of the performance calculation are (optimum):

- o Cruising Altitudes
- o Cruising Speeds
- o Vertical Speeds and/or Flight Path Angles.

2.3.3 Navigation

The Navigation function includes the following tasks:

- o Determination of the "best" present position on the basis of all available sensors' data (air, inertial, radio navigation, GNSS)
- o Automatic radio frequency tuning
- o Determination of track, distance and flight time between waypoints
- o Determination of target headings/tracks as input to the Autopilot function.

2.3.4 Vertical Guidance

The tasks of the Vertical Guidance function are similar to those of the Navigation function, however related to the vertical plane. Addtional tasks are:

- o Determination of distance and flight time to pseudo waypoints (Top of Climb - TOC and Top of Descent - TOD)
- o Determination of target speeds and target thrust settings as input to the Autothrust function.

The information provided by the FMS (e.g. flight plan, present position, tracks, distances and flight times to waypoints) is presented on the Navigation Display (ND).

3. MISSION PHASES

A military transport mission consits like a commercial flight of the following mission phases:
Take-off, climb, cruise, descent, approach, landing and perhaps go-around. Special flight phases in this context are low-level segments, which can be considered as part of the cruising phase, and the board-autonomous landing at the end of a low-level segment.

The various flight profiles including low-level segments are normally planned in advance of a mission taking into account the tactical situation.

In special situations (like detection of unexpected threats) the aircraft has to deviate from pre-planned routes. Such situations require the capability of guiding the aircraft back to a planned route as well as the capability of an onboard "on-line" re-planning of flight profiles.

3.1 Low-level Flight Segments

Low-level flight segments are integral elements of a planned mission. A low-level flight profile is defined by three-dimensional (3D) waypoints, of which the vertical coordinates are referenced to ground (AGL).

During the transition phase between cruising flight level and low-level segments, required systems checks are conducted. If all sensores and systems involved are operating normally the low-level flight phase can be initiated. The vertical reference is switched from "Baro" to "AGL".

In case of deviation from a planned flight profile the aircraft is vertically guided to a "Minimum Sector Altitude (MSA)" to be clear of terrain. For a return to the planned flight profile the aircraft, first, is horizontally guided back to the track at MSA, then being on track, the aircraft will follow the vertical profile.

The low-level flight segment is shown in Figure 3.

3.2 Board-Autonomous Landing

Board-Autonomous or self-contained landing means landing without ground-based support by radio navigational aids and without standard approach procedures, which permit defined aircraft configuration changes from cruise to landing.

Board-autonomous landing capability requires in addition to a self-contained precision navigation an energy management function, which determines the required configuration changes of the aircraft along any given flight profile.

The board-autonomous landing procedure is shown in Figure 4.

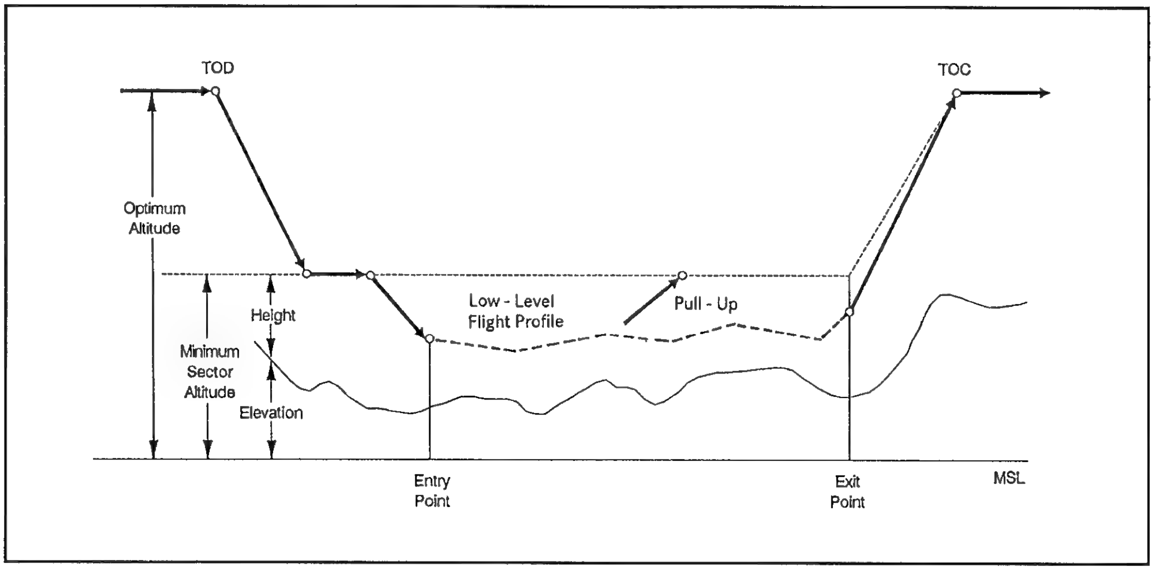

FIGURE 3: Transfer Phase between Cruising Flight Level and Low-Level Flight Segments

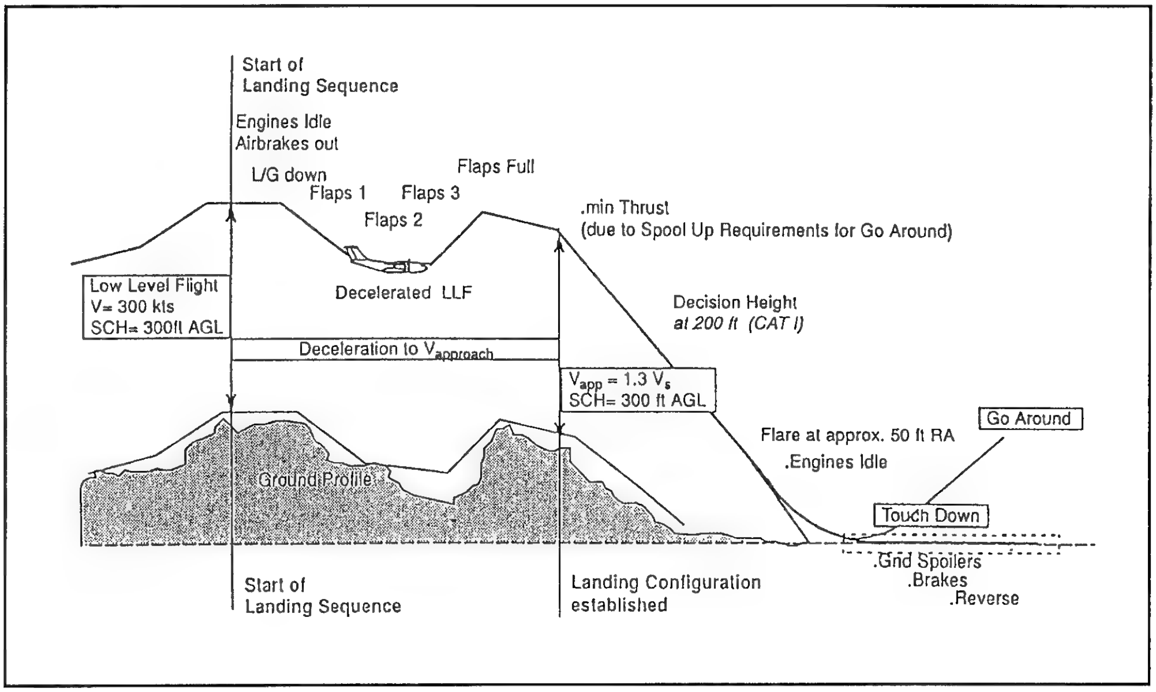

FIGURE 4: Board-Autonomous Landing Procedure

4. RESULTING REQUIREMENTS RELATED TO THE FLIGHT GUIDANCE SYSTEM

Low-level flight and board-autonomous landing capabilities require some modifications and additions to the functionality of a commercial flight guidance system, which are described below.

4.1 Fly-by-Wire System

The Flight Control System (FCS) of the future military transport aircraft will be based on the FCS features of a commercial aircraft.

Structure and functionality of a civil FbW-System can largely be transferred. Control laws will have to be adjusted to the performance (size, weight and installed agility) of the aircraft.

4.2 Autoflight Control System

4.2.1 Autopilot

The functionality of a civil AP can also be transferred. Two significant functions have to be added:

- Function "Route" performs the guidance along the planned horizontal route based on the parameters "Track" and "Lateral Deviation (Cross-Track Error)".
- Function "Profile" performs the guidance along the planned vertical profile on the basis of the parameters "Flight Path Angle" and "Vertical Deviation".

4.2.2 Autothrust

The Autothrust functions of a commercial AFCS have to be modified in the following way:

- Speed/Mach function has to be adjusted to the higher flight dynamics of the aircraft.
- Thrust function has to be extended in a way, which permits to set any defined thrust level.

4.3 Flight Management System

4.3.1 Flight Planning

Planning, modifications and re-planning of flight profiles have to be possible, during the mission onboard the aircraft by the flight crew.

A digital map containing geographical, aeronautical and tactical information is displayed on a Touch Screen Device, i.e. a Liquid Crystal Display (LCD) with a touch-sensitive surface (Figure 5).

On the basis of this information the operator can manually insert waypoints via the Touch Screen. The FMS determines the connecting straight lines (tracks) between the waypoints and the transition arcs between the tracks resulting in the horizontal (2D) route (Figure 6).

The vertical low-level flight profile is generated automatically. A Trajectory Computation function determines all parameters, which define the (4D) trajectory. These are:

- Vertical coordinates of the waypoints
- Connecting straight lines between 3D waypoints
- Transition arcs (horizontal and vertical) between the straight lines
- Tracks, distances between waypoints and times over waypoints.

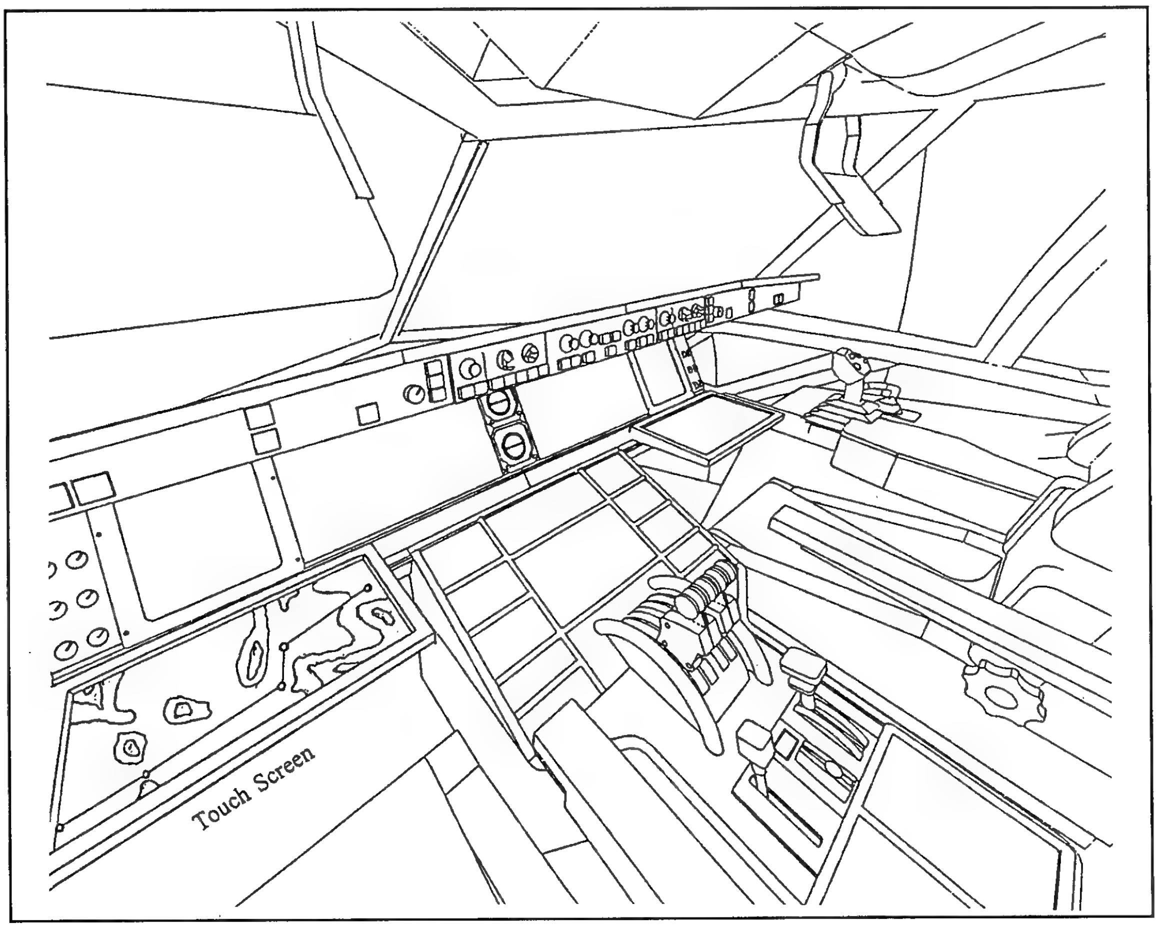

FIGURE 5: Flight Planning by Means of Touch Screen Device

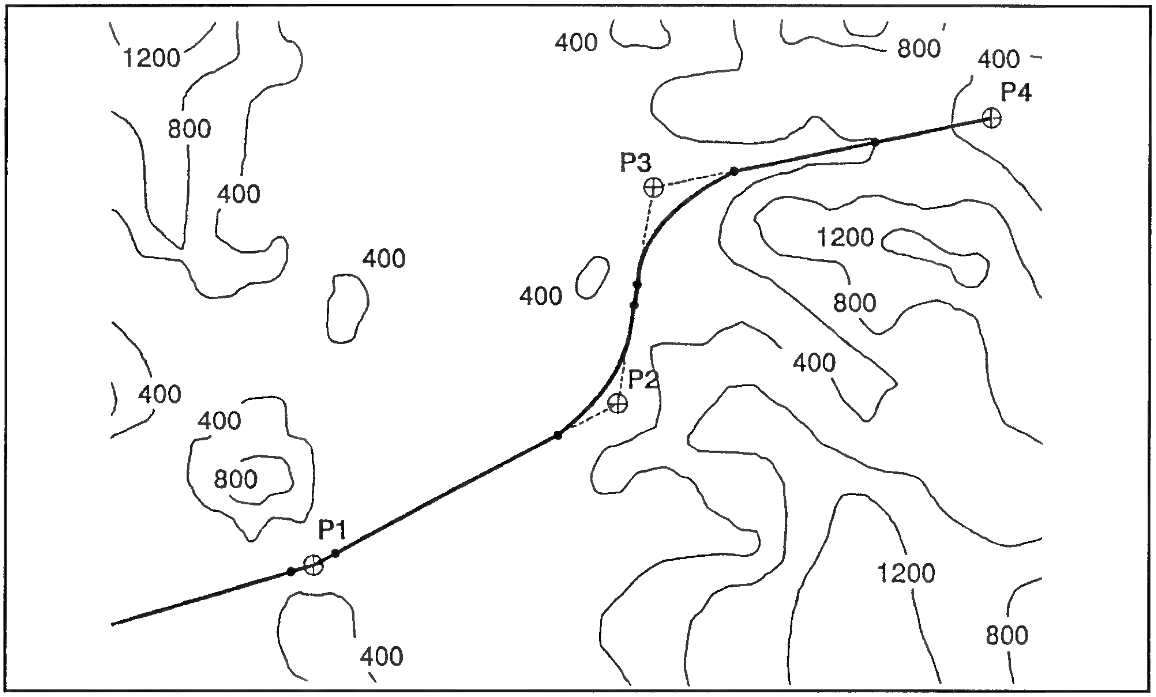

FIGURE 6: Manual-Interactive Horizontal Flight Route Planning

The resulting (4D) trajectory, which is checked for

- o Obstacle and threat clearance
- o Aircraft performance
- o Continuity,

is called "Flight Plan" and will be stored.

4.3.2 Flight Plan Execution

After activation of a fight plan, the actual aircraft position will be related to the nominal (4D) trajectory. Deviations and target values will be determined concerning:

- o Track (horizontal route)
- o Flight path angle (vertical flight profile)
- o Thrust

as input for the Autopilot and Autothrust functions.

For board-autonomous landing, additionally a "landing window" will be determined, to control the optimum aircraft configuration change between (low-level) "cruise" configuration and "landing" configuration and to issue commands for settings of flaps, speed brakes and landing gear.

4.4 Flight Guidance Information

For low-level flights the Head-Up Display (HUD) represents the Primary Flight Display (PFD). The symbology used (Figure 7) has been derived from the PFD format of an EFIS (Electronic Flight Information System). Besides the so called "Basic-T" information (attitude, speeds, altitude and heading) Pitch and Bank commands (Flight Director information) are presented. Additionally command indication for manual Thrust Setting (Thrust Director information) is provided.

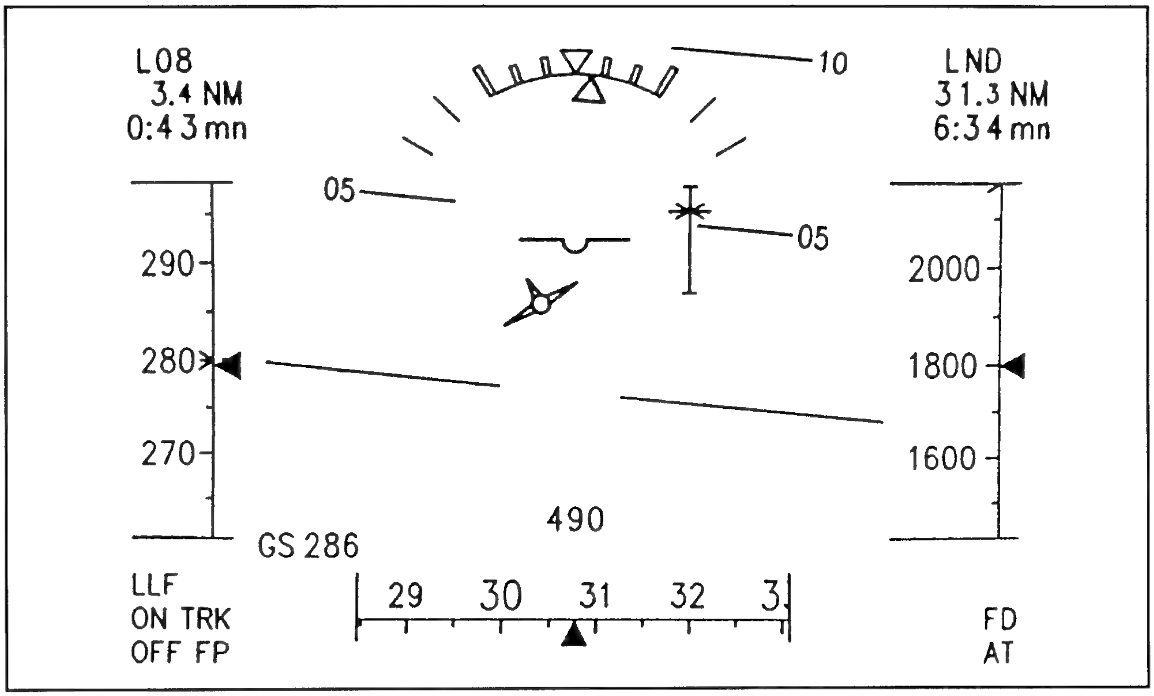

FIGURE 7: Head-Up Display (HUD) Symbology

5. RESULTS OF FIRST PILOT EVALUATIONS

Demonstrations and first pilot evaluations have been performed in the flight simulator at DAIMLER-BENZ AEROSPACE AIRBUS in Hamburg. The results obtained so far were very promising. The handling of the aircraft during low-level flight conditions was very satisfactory. The operational modes and the corresponding transitions between automatic and manual operation was well accepted.

The flight guidance information presented on both HUD und HDDs (PFDs and NDs) was also well accepted and permitted a precise and comfortable piloting of the aircraft along planned flight profiles.

The investigations have shown that low-level capabilities of a military transport aircraft can well be achieved with commercial avionics.

SELECTING A SOFTWARE DEVELOPER IN A SPECIFICATION FREE ACQUISITION ENVIRONMENT

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SUMMARY
This paper discusses a method to help in the selection of a software developer by performing in-plant capability reviews. The present trend not to use government standards, necessates the careful review of a contractor's capability and present development process.

Introduction.

Software represents a major portion of most modern weapon systems. Even though its duplication cost is very small compared to the production cost of system hardware, its development cost can exceed 50 percent of the system development cost. A seemingly minor failure in software can cause total system failure. Since software is only present in conceptual form, other than the ones and zeros stored in program memory, inspection to determine quality and consistency is very difficult. It is far more life cycle cost effective to design and develop quality software, with few if any errors, than to try to find and fix errors **after** the software is developed.

Table 1 shows data from a validated model by Krasner of Lockheed [1] indicating the cost, schedule, and expected error rates for developers at various levels of maturity as rated by the Software Engineering Institute's (SEI) Capability Maturity Model (CMM)[2] . Each project was 500 Thousand Source Lines of Code (KSLOC). The model was validated by comparison with actual project data.

Table 1 shows immediately the return on investment for process improvement for the developer and the value for the customer in reduced defects. The cost reduction would be a significant benefit for fixed price contracts, but it might be considered a negative to a cost-plus contractor.

The U.S. and NATO governments have taken a great interest in ensuring that software suppliers improve the way that they develop software. These efforts have taken many forms. ISO 9000 may be used as a basis for software process improvement[3] along with other methods discussed here. A primary effort in the U.S. has been the use of DOD-STD 2167A, *Defense System Software Development,*[4] where a systematic process for software development is spelled out, along with descriptions of the products expected at the end of each phase of development. Application of this standard allowed knowledgeable customer software engineers to observe and "audit" the development processes. These audits often took the form of document reviews.

The added interest in software quality by the customers and the hope of reduced development cost caused many software developers to search for process improvements. The Software Engineering Institute (SEI) at Carnege Mellon University, funded by the U.S. Department of Defense (DOD), has been one of the leaders in

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providing software process improvement information and measurement. The SEI Capability Maturity Model (CMM) is now widely used by companies to perform self-assessment to measure their capability and how it has changed with process improvement. The SEI also promotes the use of Software Engineering Process Groups that lead communication of process improvement activities.

The U.S. DOD's decision to eliminate most of the military specifications has changed the methods for selecting and dealing with computer software development contractors. Previously, on development contracts where DOD-STD-2167A was used, the Government customer was able to review and approve each deliverable document that represented the requirements, design, or testing before the next phase of the project could begin. While this review gave the customer control over project direction, reductions in the number of trained Government software engineers often created delays in the approval process. Contractors producing software were then forced to proceed, assuming that approval would be forthcoming. The problems that followed caused the actual software product to be disconnected from the requirements and design documentation that were supposed to be the product's source components.

With this removal of DOD military standards and acquisition streamlining staff reductions, it is necessary to totally rely on the developer who **must** check the accuracy of requirements analysis, designs, integration, and testing. Two techniques have been used to try to make this approach work. The first approach is to use Government software engineers working as team members with the developer in integrated product teams (IPT) rather than as auditors or reviewers, as was once the case. These Government IPT members facilitate communication between the contractor and the final customer (user). The second approach is to implement the source selection process to carefully select a developer who has the capability, capacity, experience, and software development process in place to produce the required high quality software without intensive oversight. Often both techniques are used on projects where the software contribution to the system will be critical.

While it has always been desirable to select a capable contractor, several impediments for intelligent selection have existed in the past. One, software engineering is a relatively new discipline and there are still different views of software processes. Two, procurement regulations have emphasized fairness in evaluating the current proposal to the extent that some past problems with a contractor might not be considered in award determination.

Performance Based Evaluations

The U.S. Air Force Aeronautical Systems Center (ASC) recognized that while companies were involved with software process improvement, contracts were with individual groups within the company. Few, if any, companies are homogeneous in their software development procedures. To evaluate the capability of individual project groups, ASC produced the Software Development Capability/Capacity Review (SDCCR)[5] . The system has now been expanded, with the aid of corporate participants, to include systems engineering capability and has been renamed as the Software Development Capability Evaluation (SDCE).[6]

The SDCE augments software process improvement as a more specific tool. A company can use the CMM to establish its process improvement plan and can be assessed against the CMM to show progress. Individual contract efforts then use the SDCE to evaluate proposed implementation groups. The SEI has also developed a Software Capability Evaluation (SCE)[7] to perform group

evaluations. While capability reviews are generally performed by the procuring agency, they may also be used by the development contractors for practice or to test their own status. In these cases it may be desirable to use an independent person who has capability evaluation experience.

An often used method for performance evaluation is past performance on completed or nearly complete contracts. In this method, the customers on previous projects report problems as well as accomplishments on the project. This method is quite valuable in determining if a contractor has a major flaw in his development process. However, it has some difficulties for a competitive procurement:

- Since different customer representatives are reporting for each offeror, the evaluations can be biased by that reporting person's attitude. That attitude for the contractor can range from hate for, to impending hire by the subject company.
- Completed contracts are seldom identical in complexity. A contractor that has problems performing on a difficult contract might actually be more capable than one who shows good performance on a simple contract.
- If incomplete data are available on past performance, the team evaluating the data tends to use its own experience with proposing contractors as data inputs. This again raises the opportunity for unequal evaluations.
- In rapidly changing technology such as software development, a contractor's capability on a project delivered several years ago may be totally out of date with current capability.

Each of these problems may reduce the objectivity and fairness of a contractor selection. However, there is a strong case for rewarding capable contractors and avoiding those who do not have or have not had sufficient capability to perform.

<u>In-Plant Capability Evaluations</u>

Both the SDCE and the SCE depend on in-plant evaluation. By taking a qualified team into each proposing plant, one can get current and accurate data that eliminate the problems just mentioned:

- By using the same identical team to visit each contractor, the capability measurement is calibrated to the same evaluator baseline. Problems with positive or negative biases of a single individual should be addressed whenever they appear, but should be solved before visits start. The use of a standard set of questions and an accepted set of answers also ensures equal treatment for all prospective contractors.
- The in-plant review evaluates how current projects are being executed. The review team should search for a range of projects that include the expected complexity of the new project. If no projects of a similar or more complex nature can be found at a contractor, then limited capability may be assumed. The team's judgment is important in issues such as this; this emphasizes the necessity for using a team that is not only expert in software development and systems engineering, but also very experienced in capability reviews.
- Incomplete data that lead to input from evaluator experience is unlikely, since each contractor is visited to obtain data.

- Since the past performance data are taken from stages of projects that are in current development or just completed, the contractor is given credit for recent process improvement activity. Most software development process improvement for U.S. contractors has peaked in the last several years.

The question is often asked, "Why not just let the prospective contractors submit a written description of their development process?" This technique would produce a less than accurate picture of the current state of practice at a given location. There is a tendency to acknowledge what one should do even if they are not doing it. Most developers acknowledge some software development methodology that would produce quality code, but human nature is to respond to schedule and budget pressures to take short cuts or eliminate critical steps. Other organizations may go so far as to hire an outside (outside the group or outside the company) individual to write the software development plan for proposal submission.

Even in-plant briefings can be misleading if verification of the current process is not observed. On one visit by the authors, the quality assurance manager, who also controlled configuration management, gave an excellent discussion of an automated system for detecting change activity so that he could be aware of new code to be analyzed and archived. The software engineers commented that with this, he became a very effective watchdog to ensure that they followed the company procedures. At the request to see a demonstration of this tool, neither the quality assurance manager nor the project software leader could log into the system. The review team concluded that the system was not as widely used on that project as had been indicated.

The purpose of in-plant reviews is not to verify that one particular methodology is being used, but that a reasonable methodology that fits the development organization is in consistent use. One of the most often used complaints about DOD-STD 2167A was that in requiring the waterfall methodology, it made object-oriented development much more difficult. However, consistency is necessary to improve a process. If a process is not consistently followed, measurements or making changes to improve it will produce inconclusive results.

At this time two different in-plant evaluation methods are in general use by the USAF. The SEI's SCE based on the CMM is preferred for evaluation of ground based and intelligence systems and AFMC's SDCE is preferred for embedded and airborne systems.

SDCE

Air Force Material Command Pamphlet 63-103 states the primary purpose of the SDCE is to "increase the probability of selecting an offeror" (proposing contractor) "capable of successfully developing software to meet request for proposal (RFP) requirements." It is intended to identify strengths and weaknesses of an offeror and not to establish a single digit rating.

The evaluation is based on six functional areas:

- Program Management
- Systems Engineering
- Software Engineering
- Quality Management And Product Control
- Organizational Resources And Program Support
- Program Specific Technologies.

Each of these functional areas are supported by critical capability areas (CCA). Figure 1 shows the relation of CCA's to the functional areas.

The CCAs are farther delineated as individual capability items in the SDCE model. Each

individual capability item has at least one question developed to help understand the offeror's capability. Table 2 shows typical critical capability items and the related questions. The C1, C2 etc. refer to capability items, and Q1, Q2, etc. refer to questions.

The SDCE method is flexible in that each project considering the purchase of software can tailor the question to be asked by selecting those CCAs that are applicable to that project. The number of questions asked for each CCA may also be reduced to fit the size and complexity of the intended contract.

The outline of questions typically used for embedded weapon system applications follows:

1. Program Management.
   - 1.1 Management Authority, Responsibility, and Accountability
   - 1.2 Program Planning and Tracking
   - 1.3 Subcontractor Management
   - 1.4 Risk Control
2. Systems Engineering.
   - 2.1 System Requirements Development, Management, and Control
   - 2.2 Computer System Architecture Design and Review Process
   - 2.3 Supportability
   - 2.4 Intergroup Coordination
   - 2.5 Systems Engineering Planning
   - 2.6 System Integration and Test
3. Software Engineering.
   - 3.1 Software Development Planning
   - 3.2 Software Project Tracking and Reporting
   - 3.3 Software Requirements Management
   - 3.4 Software Design
   - 3.5 Software Coding and Unit Testing
   - 3.6 Software Integration and Test
4. Quality Management and Product Control.
   - 4.1 Software Quality Management
   - 4.2 Software Quality Assurance
   - 4.3 Defect Control
   - 4.4 Metrics
   - 4.5 Peer Reviews
   - 4.6 Internal Independent Verification and Validation (IIV&V)
   - 4.7 Software Configuration Management
5. Organizational Resources and Program Support.
   - 5.1 Organizational Standards and Procedures
   - 5.2 Facilities
   - 5.3 Training
   - 5.4 Human Resources
   - 5.5 System/Software Engineering Environment
6. Program Specific Technologies. Questions are added here if particular unique expertise or facilities are required. Such as, expert systems, fuzzy logic, large scale geographic data bases, etc.

Review Team Selection

Since the purpose of the review team visit is to understand and evaluate the offeror's capabilities, the expertise and experience of the team is paramount. Review teams vary in size depending on the size and complexity of the project. Experience has shown that a team of three to four individuals is acceptable if at least two of the individuals are very experienced in software engineering and have experience in capability reviews. An ideal, small team might consist of:

- A leader with 10-15 years both in systems and software engineering and experience leading several SDCE's.
- A senior software engineer with 10 or more years of software engineering experience and experience participating on several capability reviews.
- A software engineer with 5 or more years of software engineering experience.
- A systems engineer from the project
- A specialty engineer from the project.

It is wise to continue to include new individuals on the teams at the third and fourth positions to provide training and experience for them to later take the leader positions.

Experience:

More than 25 in-plant visits have been conducted by the authors in the last two years. Generally these have been in support of a source (contractor) selection. However, since an in-plant review reveals weakness as well as strengths of a development organization, several reviews have been conducted for developments in progress that were experiencing difficulties. This latter type of review is often referred to as a "Red Team Review."

Visits supporting Eglin programs were accomplished with a team that normally consisted of four engineers, but the number varied from three to five. To show complete impartiality and fairness on reviews for source selection purposes, the same exact team composition and list of questions were used for all visits related to that particular source selection.

The types of organizations reviewed included commercial contractors (both prime contractors and subcontractors), U.S. Military software developers, and development activities outside the U. S.

Reviews were found valuable in pointing out strengths in particular contractor's capabilities that could be used in recommendations to the official determining the winning contractor. Specific strengths commonly found among contractor groups with a high capability included:

- Continuing effort to improve the method (process) for developing software.
- Established methodology with an ongoing enhancement plan.
- Common collection of tools for project adoption.
- Meaningful training program on methodology and tools.
- Employee support for the adopted process and its improvement.
- Collection and use of meaningful metrics.

Specific weaknesses among low capability company groups included:

- Little management interest in process improvement.
- Ad hoc selection of methodology and random adherence to it.
- Tools selected by individual developer, if available at all.
- Minimal training effort.
- Employee resistance to process improvement, if it existed.
- No easy way to determine progress in improving development.

It should be noted that two individual groups within the same corporate division can fall into different capability groups. This fact strengthens the case for reviews of individual development groups rather than relying on a single rating of a company or large division.

Conclusion

In plant capability reviews have been found to be an effective way to indicate strengths and weaknesses of potential software developers. It is a time efficient method that can be completed well within the time that other source selection factors are being evaluated. In its structured format each potential developer is treated equally. This helps to eliminate protests from those evaluated.

CMM LEVEL	DEFECTS/KSLOC	COST	DEVELOPMENT TIME
1	> 8	$33 M	40 MONTHS
2	3	$15 M	32 MONTHS
3	1	$7 M	25 MONTHS
4	0.3	$3 M	19 MONTHS
5	0.1	$1 M	16 MONTHS

TABLE 1. CMM LEVEL vs. COST

(Crosstalk Jan 1993) (Krazner/Lockheed study)

2 Systems Engineering

2.1 System Requirements Development, Management and Control

2.1.1 Development and Allocation of Requirements

C1 A systems analysis and allocation process is used to verify that the performance and verification requirements are correct and complete at each level prior to further allocation and decomposition, and to verify them as to feasibility and top-level design concept prior to allocation to software. **Q1**	**Q1** How are system and subsystem requirements defined and allocated? How are these requirements verified at each level prior to further allocation and decomposition? How are those requirements that imply digital processing and software verified as to feasibility and top-level design concept prior to allocation to software? **C1**
C2 The selected systems analysis and allocation methodology is compatible with other methodologies adopted on the program. **Q2**	**Q2** Describe how the systems analysis and allocation methodology is compatible with the systems design methodology, and with the software analysis methodology? **C2**
C3 System requirements (including test and verification requirements) are analyzed, refined and decomposed to assure complete functional allocation to hardware and software. **Q3**	**Q3** Describe the process by which system requirements are analyzed, refined and decomposed to develop a functional allocation to hardware, software, and other implementation technologies. Describe the process and specific trade studies and analyses performed to aid in deciding which requirements to allocate to hardware and which to software. **C3**
C4 When a system-level requirement is allocated to more than one configuration item (CI), a process is used to assure that the lower-level requirements taken together satisfy to the system-level requirement. **Q4**	**Q4** Describe the process which assures that when a system-level requirement is allocated to more than one configuration item (CI), the combination of the lower-level requirements meets the system-level requirement. **C4**
C5 A defined process is used to generate the initial versions of the Software Requirements Specifications (SRS) and the Interface Requirements Specifications (IRS). A process to develop and review verification requirements for each performance requirement is in place. **Q5**	**Q5** Describe the process that is used to generate the Software Requirements Specifications (SRS) and Interface Requirements Specifications (IRS). Describe the process to define verification requirements for each performance requirement as part of the requirements and definition (specification preparation) process. **C5**
C6 A process exists to identify all design documents, requirements specifications, and interface specifications across the development team, including subcontractors. **Q6**	. . . . **(From AFMC Pamphlet 63-103)**

TABLE 2. EXAMPLE QUESTIONS FOR SDCE

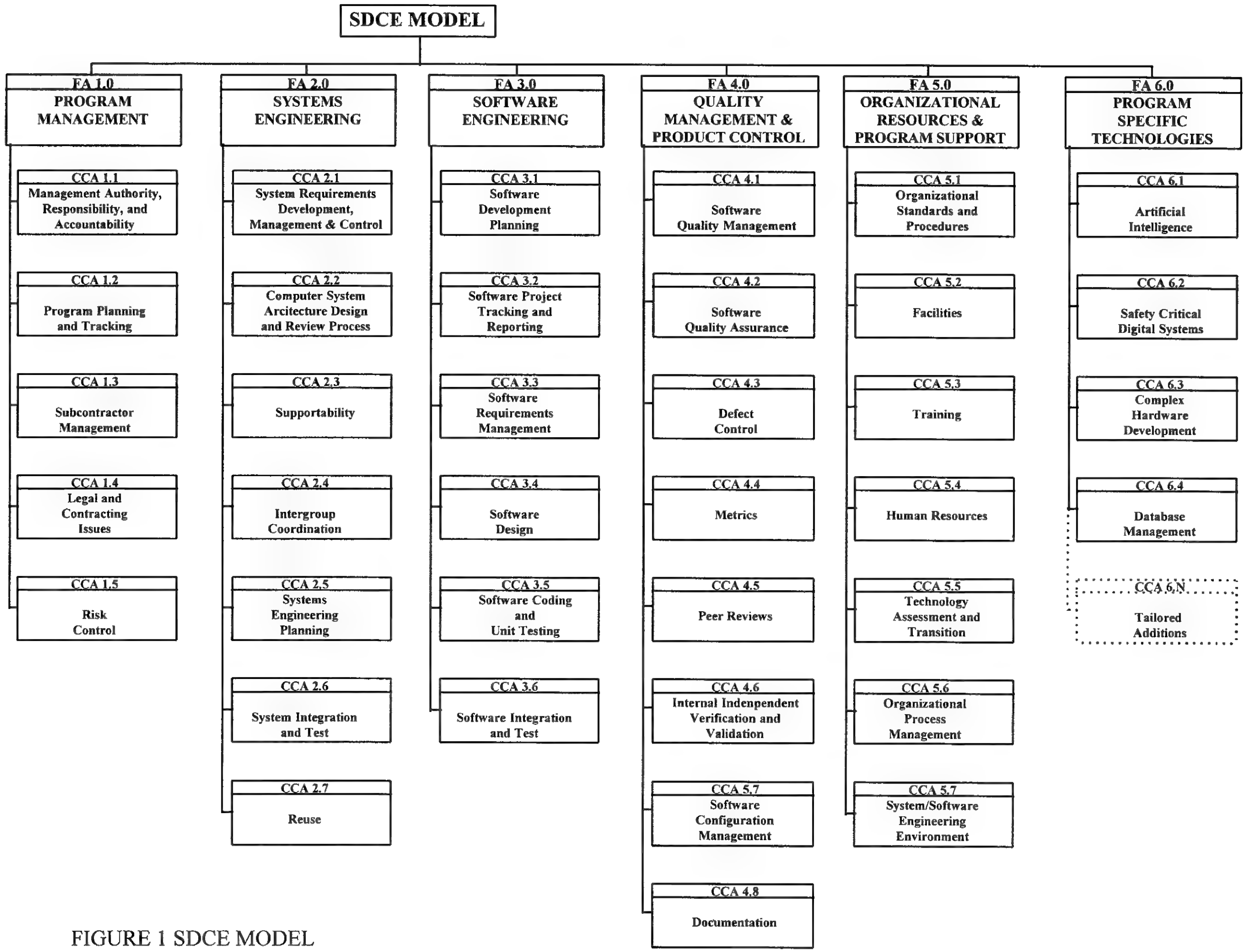

FIGURE 1 SDCE MODEL

[1] Over, J.W., "Motivation for Process-Driven Development," CrossTalk, Journal of Defense Software Engineering, Volume 40, January 1993, pp. 17-24.

[2] Paulk, M., Curtis, B., Chrissis, M., and Weber, C., "Capability Maturity Model for Software, Version 1.1," Technical Report CMU/SEI-93-TR-024, Pittsburgh, 1989.

[3] Stelzer, D., Mellis, W., and Herzwurm, G., "Software Process Improvement via ISO 9000? Results of two surveys among European software houses," IEEE Proceedings of the 29th Hawaii International Conference on Systems Sciences, Volume 1, January 1996, pp. 703-712.

[4] U.S. Department of Defense, "DOD-STD-2167A, *Defense System Software Development,"* February 1988.

[5] U.S. AFSC/ASD "Pamphlet 800-5, Software Development Capability/Capacity Review" September 1987

[6] U.S. AFMC "Pamphlet 63-103, Software Development Capability Evaluation," June, 1994)

[7] Byrnes, P., and Phillips, M., "Software Capability Evaluation Version 3.0 Method Description," Technical Report CMU/SEI-96-TR-002, 1996

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14. Abstract

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